ERDC/CHL TR-00-6

Coastal and Hydraulics Laboratory

US Army Corps of Engineers®
Engineer Research and Development Center

Study of Navigation Channel Feasibility, Willapa Bay, Washington

Report 2
Entrance Channel Monitoring and Study of Bay Center Entrance Channel

Nicholas C. Kraus, Hiram T. Arden, and David P. Simpson, editors

July 2002

With contributions by
(in alphabetical order)

Hiram T. Arden, Mitchell E. Brown, Lennie Rae Cooke, Edward B. Hands, David Hericks, Lori Oliver-Hudak, Nicholas C. Kraus, Adele Militello, Philip D. Osborne, William C. Seabergh, Vladimir Shepsis, and David P. Simpson

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Report 2 of a series

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Preface

This report is the second in a series describing a navigation channel reliability monitoring and evaluation study conducted for Willapa Bay, Washington, by the U.S. Army Engineer Research and Development Center (ERDC), Coastal and Hydraulics Laboratory (CHL), Vicksburg, Mississippi, for the U.S. Army Engineer District, Seattle (NWS). The study was established under a Partnering Agreement between the NWS and the Willapa Port Commission to investigate the feasibility of maintaining a reliable navigation channel through the entrance to Willapa Bay. Mr. Hiram T. Arden was the NWS point of contact for this study, with technical assistance and review of this report provided by Messrs. Arden, George A. Hart, Eric E. Nelson, and Robert M. Parry, NWS.

The ERDC study team was under the technical direction of Dr. Nicholas C. Kraus, Senior Scientists Group, CHL, and task-area leaders were Dr. Adele Militello, former research oceanographer, Navigation and Harbors Division (NHD), CHL, for long waves and sedimentation. Mr. William C. Seabergh, Harbors and Entrances Branch (HEB), NHD, for engineering; Mr. Edward B. Hands, formerly Coastal Evaluation and Design Branch (CEB), for morphology; Mr. David Hericks, Pacific International (PI) Engineering PLLC, for field data collection; Dr. Phillip D. Osborne for hydrodynamic and transport data analysis; and Mr. David P. Simpson, PI Engineering for local coordination. Mr. Harry Hosey and Dr. Vladimir Shepsis were the study leaders for PI Engineering.

Technical assistance in conducting the study was provided Ms. Mary Claire Allison (CEB) in support of the morphologic analysis. Word processing, editing, and formatting were completed by Ms. J. Holley Messing, CEB. Assistance at NWS was provided by Mses. Elizabeth W. Bachtel and Joyce E. Rolstad at the NWS archive; Messrs. Denny S. Mahar and Lonnie M. Reid in surveying and cartographic control; and Mr. Thomas G. Landreth, captain of the survey vessel *Shoalhunter*.

This study was conducted during the period January through December 2001 under the administrative supervision of Mr. Thomas W. Richardson, Director of CHL and Mr. Dennis G. Markle, Chief of Coastal Harbors and Structures Branch.

Contributors to this report are identified on the first page of each chapter. Dr. Kraus, Mr. Arden, and Mr. Simpson were the report technical editors. Mr. Markle was assistant to Dr. Kraus and served as administrative point of contact for this study.

At the time of publication of this report, Dr. James R. Houston was Director of ERDC, and COL John W. Morris, III, EN, was Commander and Executive Director.

Conversion Factors Non-SI to SI Units of Measurement

Non-SI units of measurement used in this report can be converted to SI units as follows:

Multiply	By	To Obtain
acres	4,046.873	square meters
cubic feet	0.02831685	cubic meters
cubic yards	0.7645549	cubic meters
feet	0.3048	meters
miles (U.S. nautical)	1.852	kilometers
miles (U.S. statute)	1.609347	kilometers

1 Introduction[1]

This chapter presents the background of a Phase II study performed for the U.S. Army Engineer District, Seattle, to determine the technical feasibility of maintaining a reliable bar and entrance navigation channel into Willapa Bay, Washington (Figure 1-1). The study was authorized by the Seattle District in cooperation with the Port of Willapa Harbor under a Partnering Agreement. The Phase I study technical report edited by Kraus (2000) was completed primarily by staff of the U.S. Army Engineer Research and Development Center (ERDC), Coastal and Hydraulics Laboratory (CHL). Field data for Phase II were collected by the Seattle District and a CHL contractor, Pacific International Engineering[PLLC] (PIE). The Phase I study was an intensive effort to understand the physical processes at the study site, collect data, and establish numerical simulation models of the waves, currents, and sediment transport at the entrance. Alternatives for creating and maintaining the most reliable entrance channel were also identified and screened.

This Phase II report describes the results of ongoing monitoring of the existing natural navigation channel, changes in bathymetry, and refinements to the numerical models. Also included is an application of the monitoring and modeling technology to the entrance channel leading from Willapa Bay to Bay Center, a small fishing harbor (Figure 1-2). The entrance area of this shallow-draft navigation channel served as a convenient surrogate for improving the predictive technology, as well as advancing understanding of sediment transport processes in the bay and the deep Willapa Bay Entrance Channel.

Included in this chapter are overviews of the study sites and discussions of related studies at Willapa Bay, study procedure, scope, and summary of the present status of this ongoing study.

Background

Willapa Bay is a large estuarine system located on the southwest Washington coast, as shown in Figure 1-1. Its spring or diurnal range tidal prism is one of the largest of all inlets on the coast of the continental United States (Jarrett 1976). The magnitude of the tidal prism is produced by the broad bay area and relatively

[1] Written by Nicholas C. Kraus, U.S. Army Engineer Research and Development Center, Coastal and Hydraulics Laboratory, Vicksburg, MS, and by Hiram T. Arden, U.S. Army Engineer District, Seattle, Seattle, WA.

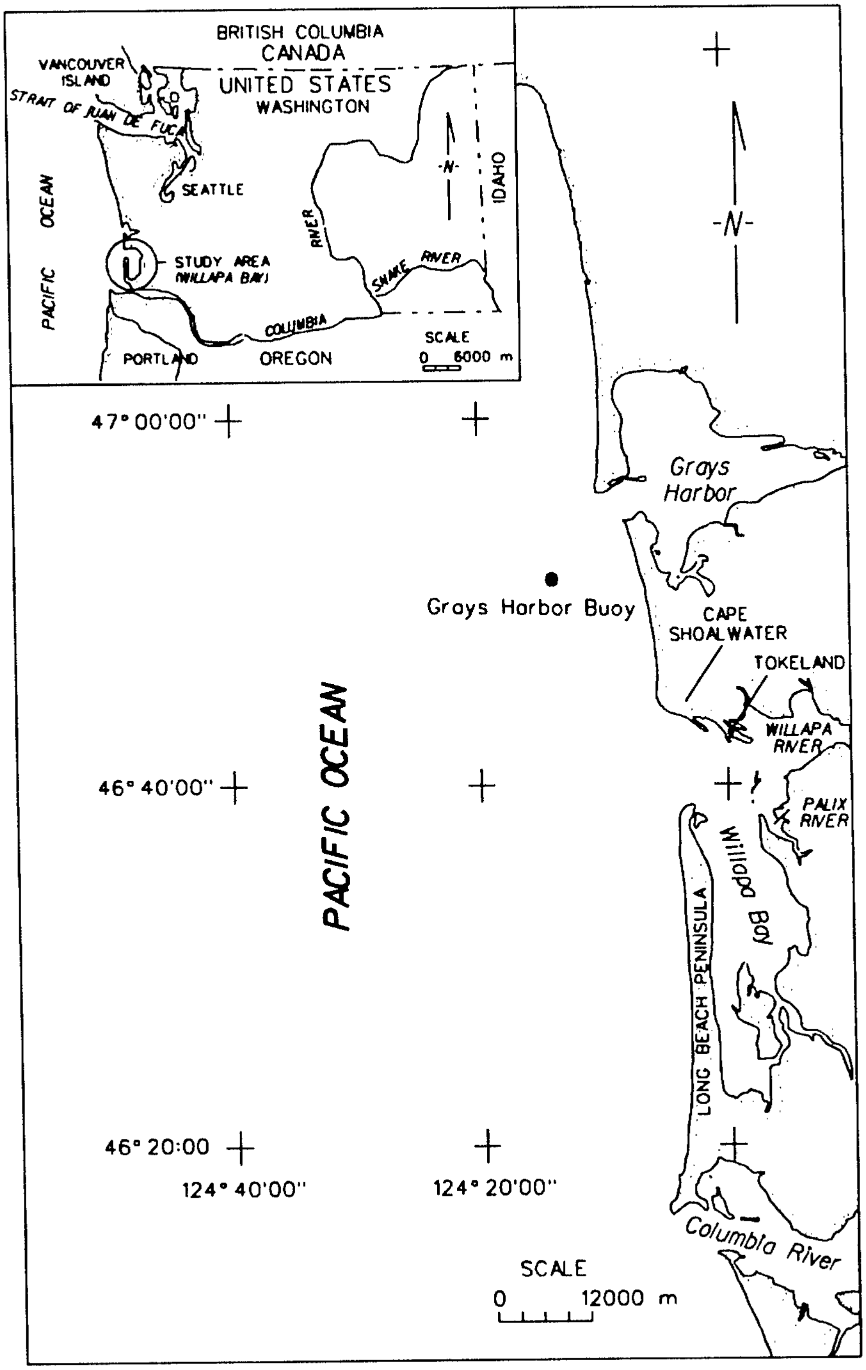

Figure 1-1. Regional location map for Willapa Bay, Washington

large tidal range at the site. The tidal range at the entrance to Willapa Bay, as measured by the National Ocean Service (NOS) of the National Oceanic and Atmospheric Administration, is approximately 2.1 m. Daily wind speed is moderate, and river inflows do not contribute significantly to the flow through the entrance. Bay hydrodynamic processes are discussed further in Chapter 2 and Chapter 6 of this report.

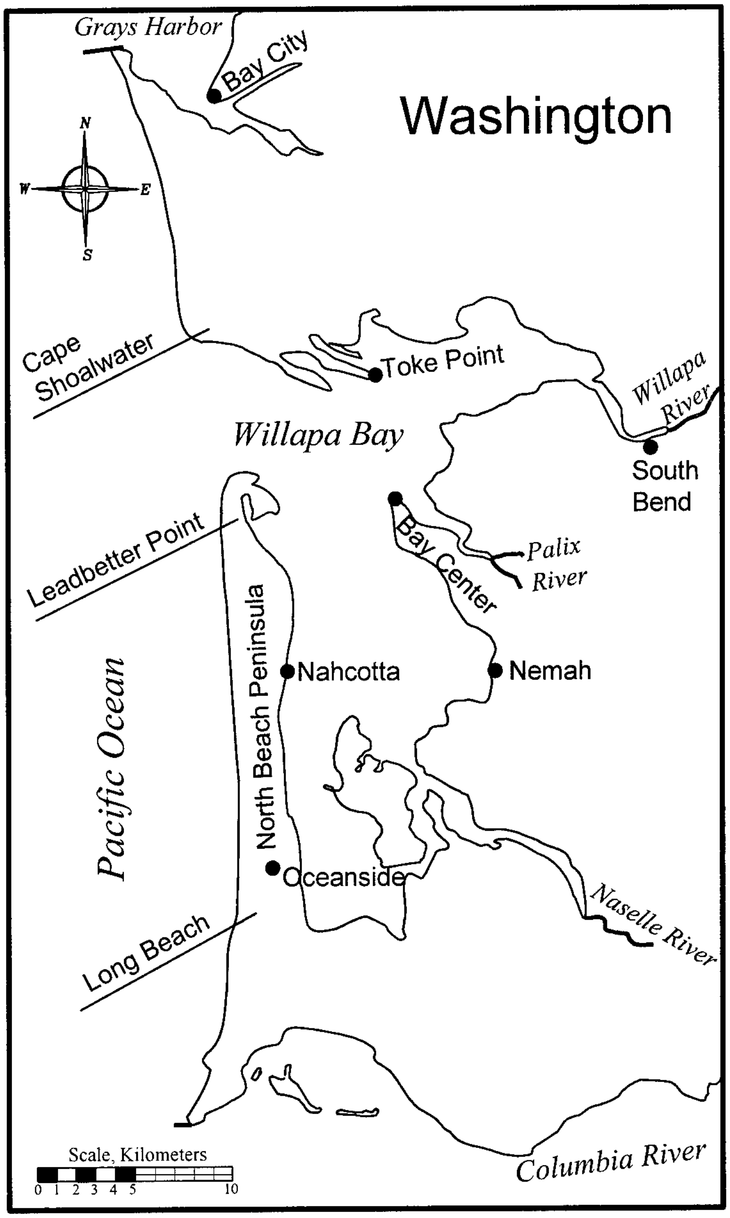

Figure 1-2. Willapa Bay and adjacent communities

Prior to the Phase I study, the Seattle District was having increased difficulty in the successful completion of routine operation and maintenance activities for navigation at the entrance to Willapa Bay, and a convenient mechanism for introducing innovative and new concepts was not available. There was growing concern from the coastal communities of southwest Washington about coastal processes at the Willapa Bay Inlet. Navigation safety continued to be of critical concern to commercial fishing and barge towing operations. Extensive coastal erosion at Cape Shoalwater (Terich and Levenseller 1986; Komar 1998) and lack of agreement on sediment transport paths and rates hindered reaching consensus for management of the various issues. Resources agencies, and maritime and

local interests demanded innovative planning and design efforts that would benefit navigation, address coastal erosion, and be sensitive to environmental resources values. Numerical simulation modeling with a reliable predictive capability was needed.

The large tidal prism and energetic waves at Willapa Bay collectively act to transport millions of cubic yards of sediment on this predominantly sandy coast, with large changes in morphology at the entrance, including several-year periodicity in spit breaching by the entrance channel (Hands and Shepsis 1999). The large-scale changes in shoals at the Willapa Bay entrance and back bay are discussed in Chapter 3, and model simulation results are presented in Chapter 4. Sedimentation in the back bay has prevented reliable, safe, shallow-draft access to commercial shellfish processing facilities located at Bay Center, WA.

During the Phase I study, a need to collect observations for modeling conditions at the other shallow-draft navigation project features was prioritized as follows based on the difficulty of maintaining adequate channel depth: Bay Center, Toke Point, and Nahcotta. Initial Phase-I data collection and modeling facilitated timely coordination, permit approval, and designation of new open water disposal sites for dredged materials at Cape Shoalwater and at the Goose Point in Willapa Bay. The persistence of shoals at the Bay Center Entrance Channel created an opportunity to transfer some effort of the Phase II study to that location, both to address channel reliability there and to further improve and validate the numerical modeling methodology. Historical survey information and data collection served as a base to model channel alignment at the Bay Center Entrance Channel, resulting in a recommendation for maintenance dredging alignment including a flared entrance and advanced maintenance dredging plus overdepth dredging.

The conception of a navigable channel at a wide and energetic inlet may seem improbable at first. However, information compiled in Chapter 3 shows that a natural but mobile channel some 25 ft[1] deep typically penetrates the outer and middle entrance bars. The tidal prism at Willapa Bay maintains a dynamically stable channel cross section that usually contains a channel approaching design requirements. Inlet stability and bulk characteristics of the entrance, as well as details of the Federal navigation channel at the entrance, are discussed in Chapter 2.

Authorizations for a Federal navigation channel through the entrance to Willapa Bay are summarized in U.S. Army Engineer District, Seattle (1971), and in Chapter 2. The existing project was first adopted in 1916 and last modified through authorization in 1954. The authorization provides for a channel over the bar of the mouth of Willapa Bay to be 26 ft deep, measured to mean lower low water (mllw), and at least 500 ft wide. A bar channel of this dimension is required for existing shallow-draft commerce. Dredging of the deep-draft river channel of Willapa Harbor was discontinued by the Seattle District in 1976 because of inadequate benefits. Maintenance dredging for shallow draft continues at Willapa Harbor for facilities at such locations as Toke Point, Bay Center, and Nahcotta, shown in Figure 1-2. Since 1976, no maintenance dredging has been required along the Federal river channel leading up from Willapa Bay to port facilities located at Raymond, Washington.

[1] A table for converting non-SI units to SI units of measure is given on page xiii.

A groin and dike were constructed in the North (ebb) Channel by the Washington Department of Transportation (WSDOT) to protect State Route (SR)-105 (Fenical, Bermudez, and Shepsis 1999). Subsequent bathymetric surveys indicate the dike and groin have altered the flow and, possibly, the location and stability of the North Channel. Action of the WSDOT Cape Shoalwater shore protection project was considered in the channel stability analysis phase of the Phase I study, and interest in the action of that structure complex continued in Phase II.

Purpose of Phase II Study

Shifting of inlet morphological features and natural channels passing through the entrance to Willapa Bay make bar navigation unreliable (U.S. Army Engineer District, Seattle, 1971, 1995[1]), and the local port cannot maintain or attract commercial users. Similarly, the back bay shoaling at the Bay Center Entrance Channel has caused critical tide delays for existing commercial fishing vessels.

The Seattle District requested ERDC, CHL to conduct a study to determine the technical feasibility of maintaining a reliable channel (28-ft depth including advance dredging and overdepth dredging allowance) over the entrance bar and into Willapa Bay. "Channel reliability" refers to stability of location and depth of the channel for an acceptable construction and maintenance cost, as well as for hydrodynamic conditions for safe passage.

Ebb currents exiting the southern arm of Willapa Bay (the arm extending toward oceanside) are directed toward the landmass of Cape Shoalwater, where they turn and run west in a relatively deep North Channel. Water exiting the tidal flats along the Willapa River also tends to flow out of the North Channel. Other channels through the bar exist ephemerally, including a Middle Channel and a South Channel, sometimes called the Leadbetter Channel in the literature. The typical locations of these channels are shown schematically in Figure 1-3. Multiple bar channels through the entrance sometimes exist, but typically one channel dominates. Properties of the natural channels, including location, persistence, and depth, are discussed in Chapter 3, based on an extensive record of bathymetry surveys spanning more than a century. The presence of these channels and their possible exploitation as a navigation channel form the basis for developing channel design alternatives, as described in Chapter 2.

Related Studies: Bay Center Entrance Channel and Cape Shoalwater Open Water Disposal

The State of Washington is conducting two studies of coastal and inlet processes of interest to the present proposed effort. The Washington Department of Ecology (WDOE), in a joint study with the U.S. Geological Survey, has made

[1] U.S. Army Engineer District, Seattle. (1995). "Willapa Bay, Washington, FY 95 bar maintenance dredging evaluation," Unpublished memorandum, 26 April 1995, Seattle, WA.

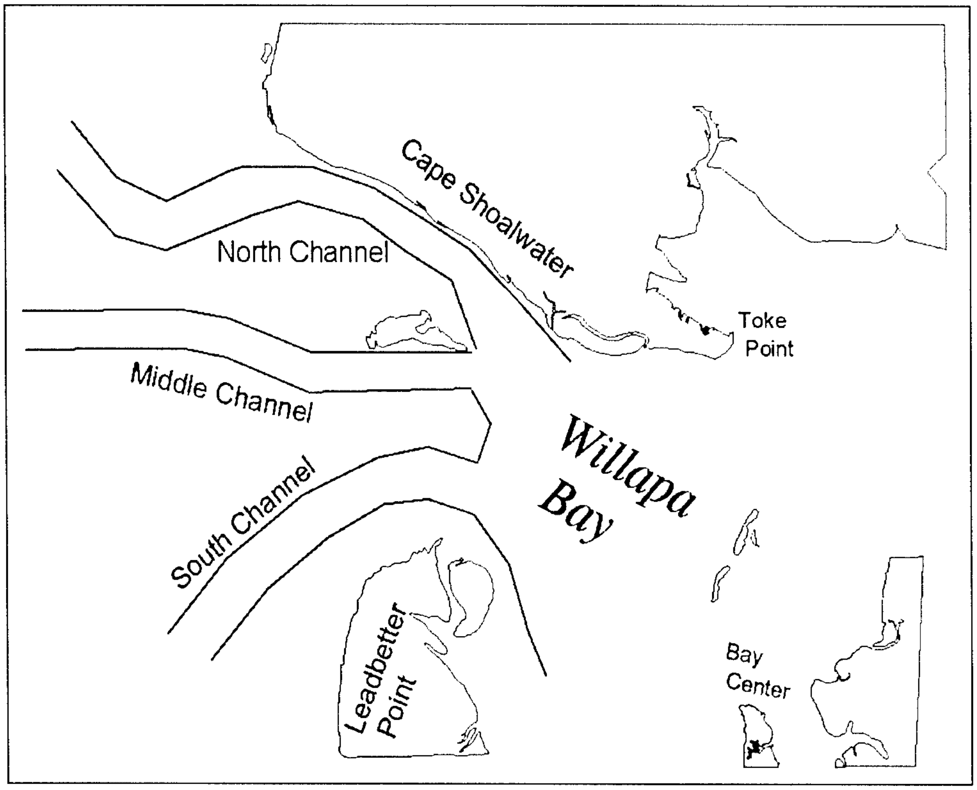

Figure 1-3. General locations and orientations of historically occurring natural entrance channels to Willapa Bay

a regional coastal assessment that includes analysis of all available historic and present data on shoreline position and bathymetry (Gelfenbaum et al. 1997; Kaminsky et al. 1999).

The WSDOT, through its lead contractor, PIE, is collecting data on waves and currents at the entrance and is monitoring coastal and inlet processes for the SR-105 Cape Shoalwater shore protection project (PIE 1997, 2001). PIE has also conducted a morphological analysis of bar channel migration, based on earlier work by the Seattle District and others (Fenical, Bermudez, and Shepsis 1999). The NOS maintains a long-term water-level station in Willapa Bay at Toke Point. As much as possible within study constraints, all relevant data were considered and joint and coordinated efforts made with these agencies and organizations for efficient and cost-effective conduct of this study.

Study Procedure

The study required efforts of several specialists who participated as a team in developing approaches and procedures and in conducting the required work. Meetings and briefings were held at the study site and at the Seattle District, as well as at CHL, with participation from the Port of Willapa, WDOE, PIE (representing local interests), Seattle District, and CHL. CHL investigators also made study site inspections and reconnaissance trips for placing instruments in and around Willapa Bay.

The study was developed as a simultaneous effort covering two general tasks. One task involved engineering, analytical, and numerical studies of the Willapa Bay Entrance Channel, as:

a. Engineering activities in consideration of entrance channel alternatives and their relation to maintenance and operation of a navigable channel. Authorized navigation features of the Willapa River and Harbor Navigation Project are extensively reviewed.

b. Evaluation of alternative designs for a reliable bar navigation channel relative to continued changes and trends observed in bar and entrance channel condition surveys. The alternatives are also placed in the context of an environmental review.

c. Analysis and interpretation of inlet morphology change.

Bathymetry data, the most basic information upon which most of the study components depend, were collected by the Seattle District's main survey boat, the *Shoalhunter*.

The other task involved data collection and numerical modeling of the current and sediment transport at the entrance channel to Bay Center. This channel, which was recently dredged, served as an additional but related site for testing numerical modeling predictive technology for the Willapa Bay Entrance Channel.

Scope of Report

This report documents the procedures, results, and conclusions of the Phase II study. Study team members describe their work in individual chapters. The chapters were planned to form a coherent approach in meeting the study objective of determining the feasibility of a reliable bar navigation channel into Willapa Bay. The approach and content of all chapters were coordinated, and an attempt was made to provide sufficient background information and cross-referencing to allow each chapter to stand alone with regard to its particular subject matter.

Chapter 2 describes the Federally authorized features of the Willapa River and Harbor Navigation Project at Willapa Bay. The chapter defines the existing Federal navigation project at Willapa Bay and discussed the history of congressional authorizations relevant to investigating channel reliability in a natural inlet. Chapter 3 summarizes recent data collection and morphologic analysis, covering both the Willapa Bay Entrance Channel and the navigation channel leading from Nahcotta Bay to Bay Center. Chapter 4 describes hydrodynamic modeling for the Willapa Bay entrance and Bay Center entrance, including sediment transport calculations for Bay Center and comparison to monitoring results. Chapter 5 presents an evaluation of alternatives for channel location and maintenance in the context of the environmental review and permitting process. Chapter 6 discusses the channel alternative designs considered through the report and summarizes present understanding based on the monitoring and modeling results obtained in this study.

Units of Measurement

Dimensions and quantities originally reported in American customary (non-SI) units on engineering documents and in the literature are retained. A table of conversion factors from non-SI to SI units is given on page xiii. Oceanographic and meteorologic measurements and calculations, such as of waves, water current, and wind speed are expressed in SI units.

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2 Congressional Authority[1]

This section summarizes the Federally authorized features of the Willapa River and Harbor navigation project located at Willapa Bay, Washington, shown in Figure 2-1. Depths are referenced to mean lower low water (mllw). The seaward channel over the bar does not appear in this figure because it varies in position by time and is marked by the U.S. Coast Guard (USCG), based on the Seattle District hydrographic surveys.

Existing Navigation Project Defined

The existing project was originally authorized in the River and Harbor Act of 1916 (U.S. Public Law 168 1916). The project was last modified by the River and Harbor Act of 1954 (U.S. Public Law 780 1954). The Federal project provides for the following:

a. A channel over the bar at the mouth of Willapa Bay, 26 ft deep and at least 500 ft wide. Overdepth of 2 ft is allowable.

b. A channel 24 ft deep and 200 ft wide, from deep water in Willapa Bay to the base of Ferry Street in South Bend, then 300 ft wide to the westerly end of the Narrows, then 250 ft wide to the forks of the river at Raymond, including a cutoff channel 3,100 ft long at the Narrows.

c. A channel 24 ft deep and 150 ft wide up the South Fork to the deep basin above Cram Lumber Mill, and up to the North Fork to 12th Street, with a turning basin 250 ft wide, 350 ft long, and 24 ft deep.

d. A channel 10 ft deep and 60 ft wide from deep water in Palix River to Bay Center Dock.

e. An entrance channel 15 ft deep and 100 ft wide, and a mooring basin 15 ft deep, 340 ft wide, and 540 ft long, adjacent to port wharf at Tokeland.

f. An entrance channel at Nahcotta 10 ft deep, 200 ft wide and a mooring basin 10 ft deep and 500 ft wide, protected by a rubble-mound breakwater approximately 1,600 ft long.

[1] Written by Lori Oliver-Hudak and David P. Simpson, Pacific International Engineering PLLC, Edmonds, WA.

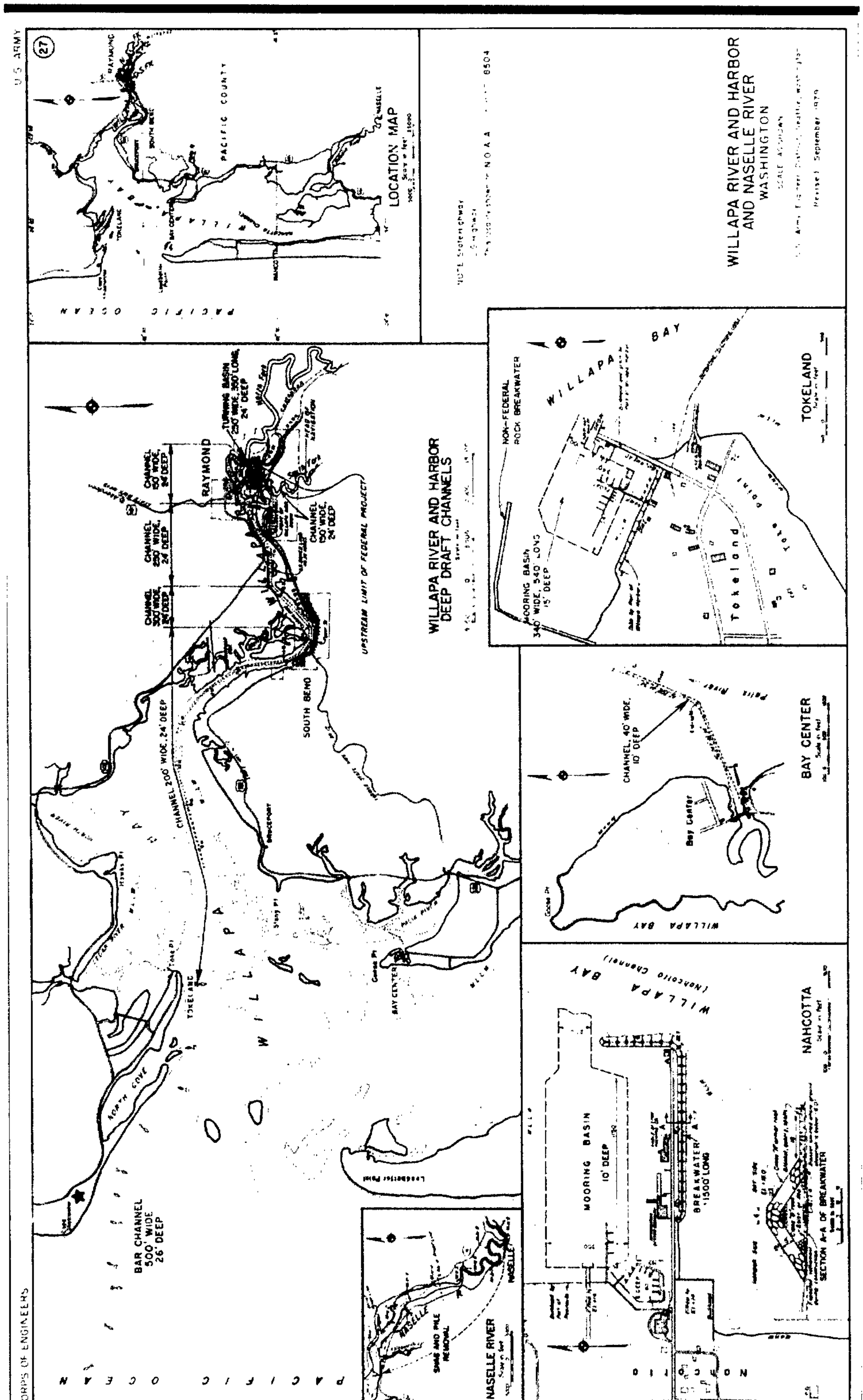

Figure 2-1. Willapa River and Harbor navigation channels (project map, Seattle District)

Congressional Authorizations of Bar and Entrance Channel

A previous phase of this study (Kraus 2000) analyzed the engineering feasibility of maintaining a reliable navigation channel through the entrance to Willapa Bay. The present report analyzes the remaining alternatives for arriving at a final recommendation of a preferred alternative in a later study phase. Each of the presently remaining action alternatives concerns provision for a navigation channel over the bar at the mouth of Willapa Bay. Thus, further inquiry into the scope and history of the congressional authorization for the navigation project focuses on the bar at the mouth of Willapa Bay, as described previously, in subsection (*a.*).

The River and Harbor Act of 3 March 1909 authorized the examination of the bar at the mouth of Willapa Bay. The preliminary examination noted that the depth of water over the ocean bar was 27 ft at mllw, with a channel width adequate to the needs of commerce (in House Document 524, 2, 4; U.S. Congress 1910). The District Engineer recommended that a survey of the entrance be made, as it would be of future material value in the event that the present depths over the bar decreased or became inadequate because of the increased draft of vessels seeking to use the port (in House Document 524; 4; U.S. Congress 1910). In March 1913, Congress agreed and authorized a survey and preliminary examination of Willapa Harbor and Bar (U.S. Public Law 264 1910).

The preliminary examination of Willapa Harbor and Bar submitted to Congress in January 1916 revealed that the depth over the bar was 23 ft at mllw, which exceeded the depth available in the Willapa River by 5 ft (in House Document 555, 2, 3; U.S. Congress 1916). Congress had not yet acted upon an earlier request to increase the depth of the Willapa River. Until Congress acted upon the request, the District Engineer recommended that a decision on increasing the depth over the bar be deferred, noting that vessels with a 30-ft draft were able to safely enter the harbor under favorable conditions and that nearly all of the commerce comes from the river (in House Document 555, 4, 6; U.S. Congress 1916). The timing for crossing the bar could therefore be chosen for most vessels having a loaded draft to 30 ft.

Another examination and survey of Willapa Harbor was performed under authorization contained in the River and Harbor Act of 3 March 1925 (U.S. Public Law 585 1925). Local interests were seeking a depth of 30 ft over the bar, either through dredging or jetty construction (in House Document 565, 2, 4, 5, 10, 11; U.S. Congress 1926). The survey confirmed that the entrance to Willapa Harbor is located in the northern part of the bay and is approximately 4.3 miles wide between Cape Shoalwater on the north and Leadbetter Point on the south. The entrance is obstructed by "a bar lying about 3 miles outside" (in House Document 565, 5; U.S. Congress 1926). The report also noted that the channel over the bar shifted from north to south over a cycle of about 20 to 30 years (in House Document 565, 4; U.S. Congress 1926).

In this report, the District Engineer reported to Congress that commerce was not of the character or magnitude to justify the expense of creating a channel over the bar materially deeper than what existed. However, the existing commerce was sufficient to justify a channel with a dependable depth of 23 ft, with a normal

tidal range of 8 ft. In this report, according to House Document 565, 3 (U.S. Congress 1926), the Chief of Engineers recommended:

> . . . that modification of the existing project for Willapa Harbor, Wash., is deemed advisable so as to provide for a channel over the bar at the mouth of Willapa Bay, 23 ft deep at mean lower low water and of such width as is economically obtainable, at whatever location is dictated from time to time by existing conditions at the bar.

On 21 January 1927, Congress concurred with the report and authorized the Willapa Harbor project "in accordance with House Document 565" (U.S. Public Law 560 1927).

The Committee on Rivers and Harbors of the House of Representatives by resolution in 1930 requested the Board of Engineers review "House Document Numbered 706, 63rd Congress, 2nd Session, and House Document Numbered 565, 69th Congress, 2nd Session." Pursuant to this request in 1932, in House Document 41, 3, 5, 9 (U.S. Congress 1932), the Chief of Engineers recommended modification of the existing project as follows:

> . . . that the existing project for Willapa River and Harbor, Washington, be modified so as to provide for a channel over the bar at the mouth of Willapa Bay 26 ft deep, with a minimum width of 500 ft, at an estimated cost of $80,000 annually for the maintenance in addition to that now required.

In recommending a depth of 26 ft, the Division Engineer noted that the channel should provide for "a suitable project depth which can, with reasonable certainty, be carried through the winter by overdepth dredging during the summer, and maintenance work should be conducted on this basis" (in House Document 41, 9; U.S. Congress 1932).

In 1933, the Committee on Rivers and Harbors of the House of Representatives again passed a resolution requesting that the Board of Engineers review its earlier reports on Willapa Harbor and determine whether further modifications were necessary in (U.S. Congress 1933). In reporting back to Congress, the Chief of Engineers did not concur with the Board of Engineers recommendations. Instead, he concurred with the Seattle District and its Division and stated, in House Document 37, 3 (U.S. Congress 1934) it was:

> . . . advisable to provide for straightening the Narrows by a cut-off channel 200 ft wide, 24 ft deep, and about 3,100 ft long, . . .

The River and Harbor Act of 1935 (U.S. Public Law 409 1935) then authorized the work recommended in the 1932 and 1934 House reports.

Current Congressional Authorization

The existing Congressional authorization for the Willapa River and Harbor project, with respect to the entrance bar, is for creation of a channel over the bar at the mouth of Willapa Bay. The location of the channel depends on the depth over the existing bar, but is to be 26 ft deep (plus allowable overdepth dredging), with a minimum width of 500 ft.

Regulations governing navigation and dredging operations and maintenance policies make it clear that overdepth dredging is permitted for a maximum of 2 ft to allow for inaccuracies in the dredging process in coastal regions (Engineering Report 1130-2-520).

Evaluation of Navigation Channel Alternatives

The screening process described in the previous navigation feasibility study (Kraus 2000) produced basic alternative groups: (a) North Fairway; (b) State Route (SR)-105 dike modification; and (c) Middle Fairway. Each alternative involves maintaining a channel over the bar at the mouth of Willapa Bay. Congressional documents describe the bar as being located 3 miles outside the entrance, with the entrance falling between Cape Shoalwater and Leadbetter Point. Each alternative is analyzed in the following subsections to determine if the alternative falls within the existing Congressional authorization.

North Fairway (bar and entrance)

Alternative 3A: 26-ft-deep (with 2-ft overdepth) by 500-ft-wide channel, fixed location.

Alternative 3B: 26-ft-deep (with 2-ft overdepth) by 500-ft-wide migrating channel, with a minimum 1,500-ft width in S-curve.

Alternative 3F: 38-ft-deep by 1,000-ft-wide channel, fixed location.

Alternative 3G: 38-ft-deep by 1,000-ft-wide migrating channel, with a minimum 1,500-ft width in S-curve.

Alternatives 3A or 3B could be implemented without modification of existing Congressional authority, which provides for dredging to 26 ft with 2 ft of allowable overdepth dredging. The present study focused on dredging to 28 ft (26 ft with 2-ft overdepth), in recognition of the existing authority, plus customary overdepth dredging. The existing authority provides for a channel at least 500 ft wide; thus, the width of the channel alternatives conforms to the existing authorization. The existing authority is sufficiently broad to provide for a fixed channel or a migrating channel, because the authority permits dredging a channel at whatever location is dictated by the conditions at the bar.

Alternatives 3F and 3G would require modification of the existing authority to increase the depth of the authorized channel from 26 ft to 38 ft. The existing authority provides for a channel at least 500 ft wide. Thus, Alternatives 3F and 3G are not in conflict with authorized width.

SR-105 dike

Alternative 3H-a: 28-ft-deep by 500-ft-wide channel.

Alternative 3H-b: 28-ft-deep by 500-ft-wide channel, with the SR-105 dike raised from 18 ft mllw depth to 2 ft mllw depth.

Similar to Alternatives 3A and 3B, sufficient authority exists to implement Alternative 3H-a (dredge to a depth of 26 ft, plus allowable overdepth dredging).

The existing authority provides for a channel at least 500 ft wide; thus, the width of the channel alternative conforms to the existing authorization.

However, Alternative 3H-b requires other considerations. The groin and underwater dike in the North (ebb) Channel at the entrance of Willapa Bay were constructed in 1998 by the Washington State Department of Transportation (WSDOT), with funding assistance from the Federal Highway Administration (FHWA). The purpose of the project was to protect SR-105, the only transportation link connecting Tokeland and the Shoalwater Indian Reservation with Grayland and Westport. The structure is maintained by WSDOT, and maintenance is expected to continue.

Bathymetric measurements made during the course of monitoring the SR-105 project indicate that the structure may be responsible for the observed deepening of the south side of the north channel just seaward of the SR-105 project. This deepening and southward movement may contribute to development of a reliable navigation channel into Willapa Bay. Thus, Alternative 3H-b was added to account for the potentially beneficial influence of the WSDOT structure in promoting favorable hydraulics for a bar and entrance channel. Additional evaluation of the response of the channel to the groin would be required.

If this alternative were selected, the groin and underwater dike may be determined essential for promoting a reliable channel. Modification of current Congressional authority to include maintenance and or modification of the existing groin and underwater dike may be necessary.

Existing maintenance arrangements of the SR-105 project by WSDOT may be adequate. However, modifications to the structure to support the navigation project may be required. For example, an increase in the height of the dike might be necessary/justified to optimize the navigation channel dimensions and alignment. Under these circumstances, modification to the existing authority to include this feature and maintain it for navigation may be necessary.

A study of improvements to existing non-Federal infrastructure (dike/groin) construction of recommended improvements with subsequent Federal maintenance may also be justified (Engineering Pamphlet 1165-2-1). Congressional authorization would be required for construction of new improvements (increasing the dike crest elevation).

A third possibility is to consider this improvement a New Reconstruction Project. The New Reconstruction Project program is applicable if the proposed work will ensure that the project continues to deliver the full benefits intended by Congress at the time of authorization, without expanding the scope, function, or purpose of the project (Engineer Circular 11-2-177). Typically, this program applies to older projects that are no longer performing satisfactorily.

Middle Fairway (bar and entrance)

Alternative 4A: 28-ft-deep (26 ft with 2-ft overdepth) by 500-ft-wide channel.

Alternative 4E: 38-ft-deep by 1,000-ft-wide channel.

Alternative 4A could be implemented without modifying existing Congressional authority, providing for dredging to 26 ft with a maximum of 2-ft

overdepth dredging to allow for inaccuracies in the dredging process in coastal regions. The existing authority provides for a channel at least 500 ft wide, and the width of the proposed channel conforms to the existing authorization. The existing authority is sufficiently broad to provide for either a fixed channel or a migrating channel because the authority permits dredging a channel at whatever location is dictated by the conditions at the bar.

Congressional approval to modify the existing authority to maintain a channel at 38 ft, rather than the existing authorization for 26 ft, is required to implement Alternative 4E. The existing authority provides for a channel at least 500 ft wide, and thus the width of the channel alternative conforms to the existing authorization.

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3 Monitoring of Inlet Physical Processes[1]

Introduction

This chapter updates the data and analysis of geomorphologic trends and the estimates of the sedimentation rates for navigation channel alternatives that were selected in the screening as described in Report 1 (Kraus 2000) and Chapter 1 of the present report. Data collection focused on the Bay Center Entrance Channel because the maintenance dredging schedule coincided with the need to collect data to verify the sediment transport model that is being applied at the Willapa Bay entrance. Sediment transport and bathymetric change were calculated over the Willapa Advanced CIRCulation (ADCIRC) model grid for specific storms in Report 1 (Kraus 2000), but the size of model domain and the rate of measurable bathymetric change make it impractical to verify the model with multiyear bathymetric surveys.

The Bay Center Entrance Channel, however, is a smaller feature within the original model grid and has responded to past maintenance dredging by rapidly trapping sediment transported to the channel. A field data collection program was designed to document pre and postdredging current, water level, and bathymetric information in the channel to verify the numerical model in the limited region of Bay Center. Greater certainty could then be gained in transport simulations throughout the Willapa Bay model. This chapter presents those bathymetric and hydrodynamic data collected during 2000-2001.

Bathymetry of Bar and Entrance Channel

Report 1 identified the cyclic geomorphologic processes active at the Willapa Bay entrance and developed estimates for sedimentation rates for the screened channel alternatives of the North and Middle Fairways (Hands 2000). The study showed that growth of a spit, southward from Cape Shoalwater and subsequent dissection of the spit near its proximal end have been repeated in seven cycles in the years 1933 to 1998. Northward migration of the North Channel and erosion of the North Cove increased during the time that the North Channel exited to the ocean in a more northerly orientation. Bathymetric analysis identifies a channel design (location and dimensions) that can reliably serve navigation and be economically maintained, as well as meet environmental and other criteria.

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[1] Written by David P. Simpson, David Hericks, and Philip D. Osborne, Pacific International Engineering[PLLC], Edmonds, WA.

Analysis of the year-to-year volumes within the dredging template of the alternatives provides a means of projecting likely future dredging requirements of the alternative alignments.

Hydrographic surveys were made of the bar and entrance channels by the Seattle District survey boat, *Shoalhunter*, in August 1998, April 1999, October 1999, May 2000, September 2000, and March 2001. The 1998 survey of Willapa Bay included airborne data collection as well as bathymetric surveys and provided bathymetry suitable for representing the entire estuary with a computational grid developed in the study presented in Report 1. Later surveys were limited to the north bay and entrance area to document the condition of the North Channel and the bar. The Seattle District surveys were made with a 200-kHz transducer emitting a single 3-deg beam. Track lines were oriented generally east-west at a spacing of 2,000 ft. Bathymetry surveyed from 1998 through 2001 are shown in Figures 3-1 through 3-6 where water depths are referenced to mean lower low water (mllw) corresponding to the Toke Point tide gauge. The horizontal datum is NAD 83, Washington State Plane – South.

Report 1 identified the North Channel and Middle Channel as alternatives requiring further study to recommend a plan for restoring a commercial navigation channel. Analysis made during the course of the feasibility study documented the rapid adjustment of the North Channel in the vicinity of the underwater dike constructed at North Cove, as part of the Washington State Department of Transportation (WSDOT) project to protect SR-105 (Figure 3-6). The type of bathymetry changes observed in the surveys of August 1998 through October 1999 indicated that the North Channel could be

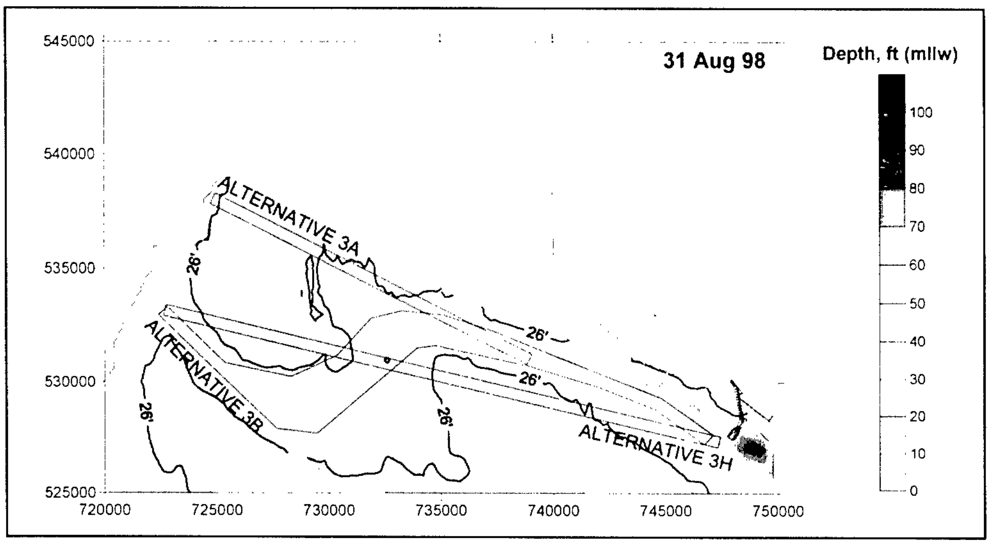


Figure 3-1. Willapa Bay bar and entrance bathymetry, August 1998

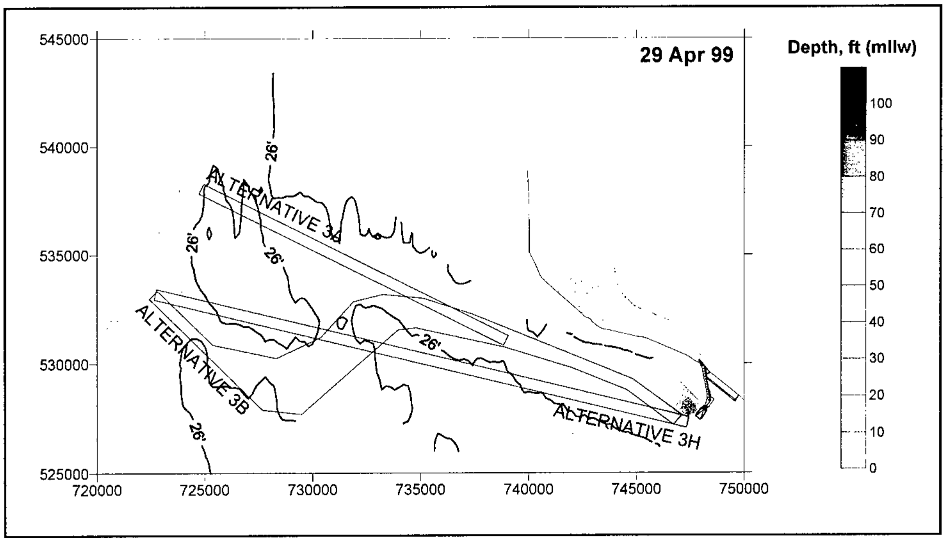


Figure 3-2. Willapa Bay bar and entrance bathymetry, April 1999

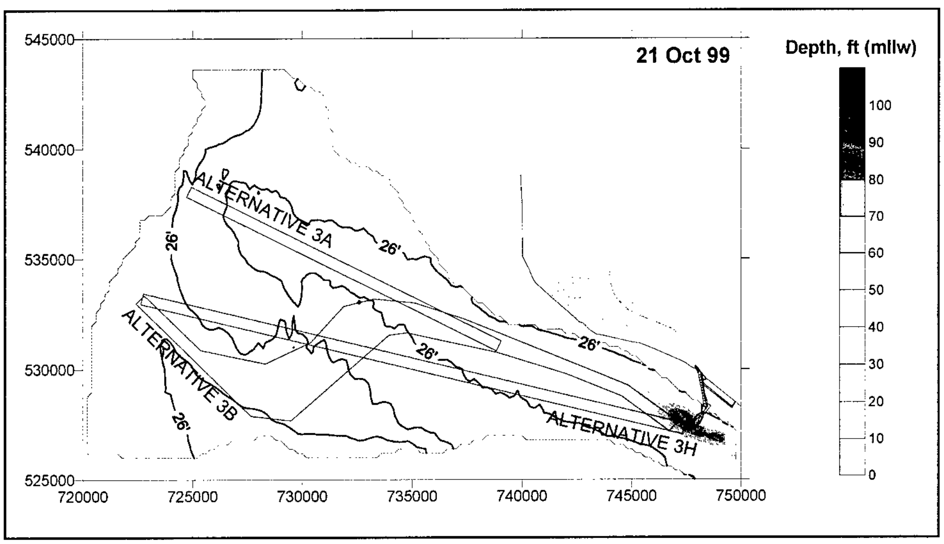


Figure 3-3. Willapa Bay bar and entrance bathymetry, October 1999

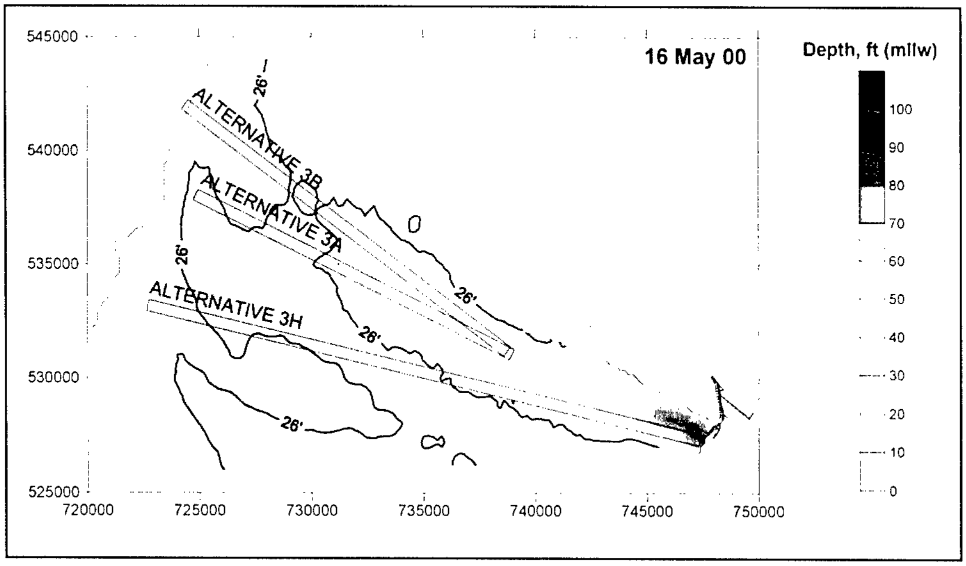


Figure 3-4. Willapa Bay bar and entrance bathymetry, May 2000

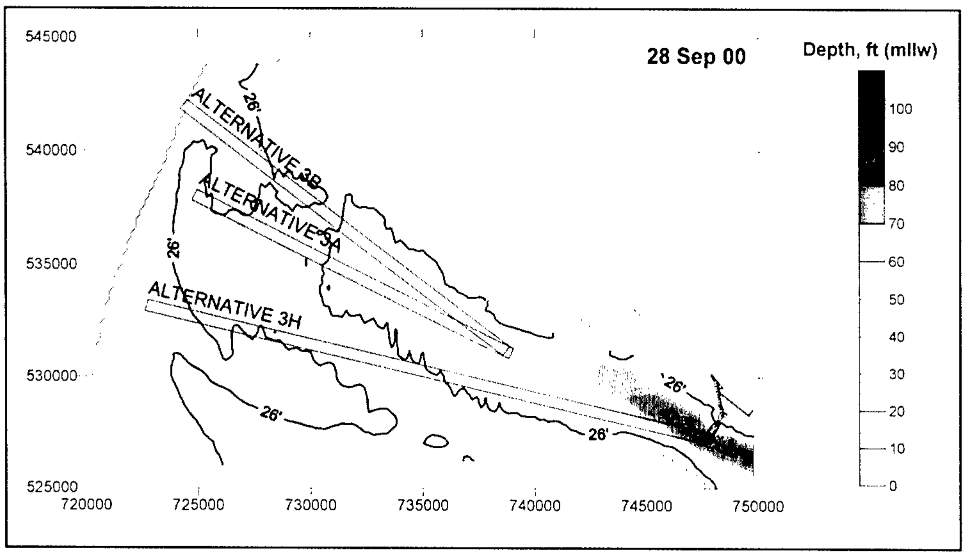


Figure 3-5. Willapa Bay bar and entrance bathymetry, September 2000

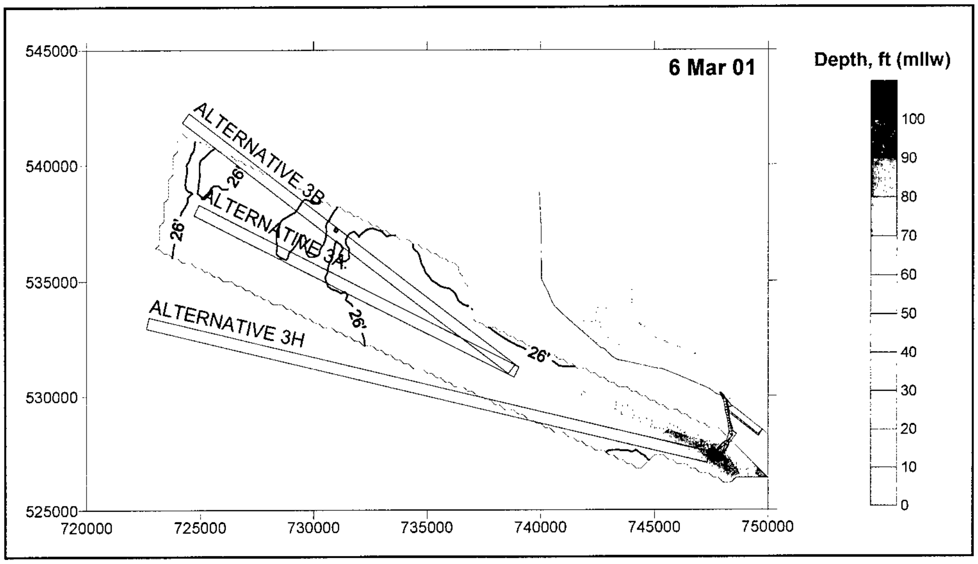


Figure 3-6. Willapa Bay bar and entrance bathymetry, March 2001

developing an alignment northwestward from the underwater dike that is different from those of Alternatives 3A and 3B. After completing Report 1, bathymetric surveys at the Willapa Bay entrance were made in May and September 2000, and in March 2001. These new surveys are compared to the previous surveys in the analysis that follows. Trends in bathymetric changes (geomorphologic changes) and updates of sedimentation rate estimates determined with methodology established in Report 1 are discussed. One purpose is to determine if self-scouring channels are developing in the alignment and if the channel dimensions are consistent with requirements of a commercial navigation channel at the entrance to further narrow the range of channel alternatives.

Morphodynamics of features in the Willapa Bay entrance as analyzed in Report 1 described cycles of channel migration that were interrupted and restarted with a new northwesterly channel alignment at intervals of 7 to 27 years. Superimposed on this trend of channel and shoal movement is a random variation of channel and shoal elevations and dimensions. Consequently, surveys in the 2-year interval since construction of the SR-105 dike are not adequate to confidently distinguish progressive channel changes from the random changes. However, the dike is expected to influence the hydraulics and sediment transport, and, therefore, the morphology of the North Channel. Bathymetric change is analyzed in the section "Interpretation of Bathymetric Change" by dividing the area into two reaches separated by the E735000 state plane coordinate (Figure 3-6).

Bathymetry of SR-105 Project Area

The SR-105 Emergency Stabilization Project is a WSDOT project located along the north shore of Willapa Bay at North Cove (Figure 3-6). Dredged material disposal sites were previously located in the vicinity of the project, which indicates that the site is dispersive for disposed sediments (erosive site). The SR-105 structures consist of an underwater rock dike, a rock groin

connecting the dike to the shore, and dredged sand placed as additional erosion buffer for the highway embankment on the eastern side of the groin. The underwater portion of the construction is referred to in this report as the dike, and the above-water portion as the groin. The project was constructed in the summer and fall of 1998 to arrest the northward movement of the North Cove shoreline at a location known as Washaway Beach and to prevent the collapse of the SR-105 road embankment into Willapa Bay (Shepsis and Phillips 1998). The structures have prevented the loss of the highway at that location, accelerated the tidal flow in the vicinity of the tip of the dike, and changed the pattern of bottom scour and deposition in the vicinity of the underwater dike. PI Engineering collected and analyzed coastal, oceanographic, and geomorphologic data through July 2001 as part of the monitoring program for the WSDOT to assess engineering and environmental performance of the project (PI Engineering 2001a).

Bathymetric surveys were made across the North Channel along five transects extending from 3,100 ft northwest to 3,100 ft southwest of the SR-105 dike 22 different times from 3 September 1997 to 21 January 2001. Survey data quality was verified by running tie lines perpendicular to the primary survey lines. All data acquisition systems, including the echo sounder, heave/pitch/roll sensor, and the onboard computer systems, were calibrated before and after each bathymetric survey. Transect locations and cross-section plots of 3 September 1997 and 13 May 2001 are compared for each transect in Figure 3-7. Bathymetry surveyed as part of the SR-105 monitoring from 1998 to 2001 (PI Engineering 2001a) provides more frequent documentation of depths near the SR-105 structures than does the bar and entrance channel surveys shown in Figures 3-1 through 3-6. Observations of channel morphologic change exhibited in the two data sources are consistent in that they show southward migration of the channel reach just seaward of the dike and intensifying scour both east and west of the dike.

Topographic surveys cover more than 16,500 ft along the North Cove shoreline, including the project area and adjacent beaches. Surveys have been repeated along fixed transects and are tied into four WSDOT monuments located upland. The surveys are designed to identify changes in the upper beach morphology and shoreline position.

Current in North Channel

The current in the North Channel was measured as the bathymetric survey boat transited the channel cross section. The current meter, a SonTek Acoustic Doppler Profiler (ADP), records flow speed at points vertically through the water column. Data from the transect are processed together with the boat position to yield a pattern of flow speed through the section of channel. ADP transects were made at the time of surveying in April 2000 to obtain the velocity structure in a vertical section along the cross-channel transects. The along-channel velocity pattern at five transects measured at the peak ebb current on 12 April 2000 is shown in Figure 3-8. The velocity pattern measured at the peak flood current on 11 April 2000 is shown in Figure 3-9.

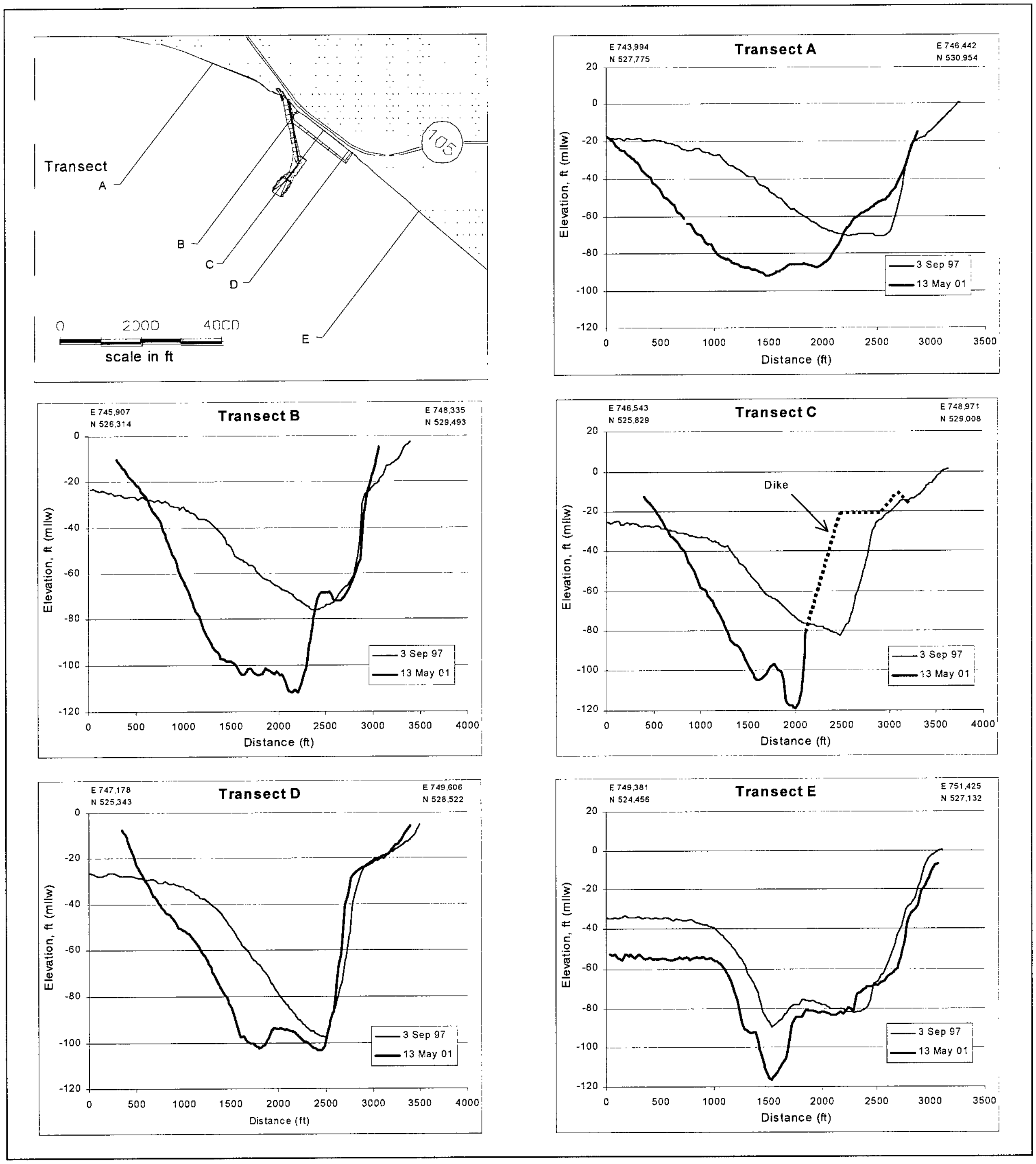


Figure 3-7. Cross-section comparisons at SR-105 dike, September 1997 and May 2001

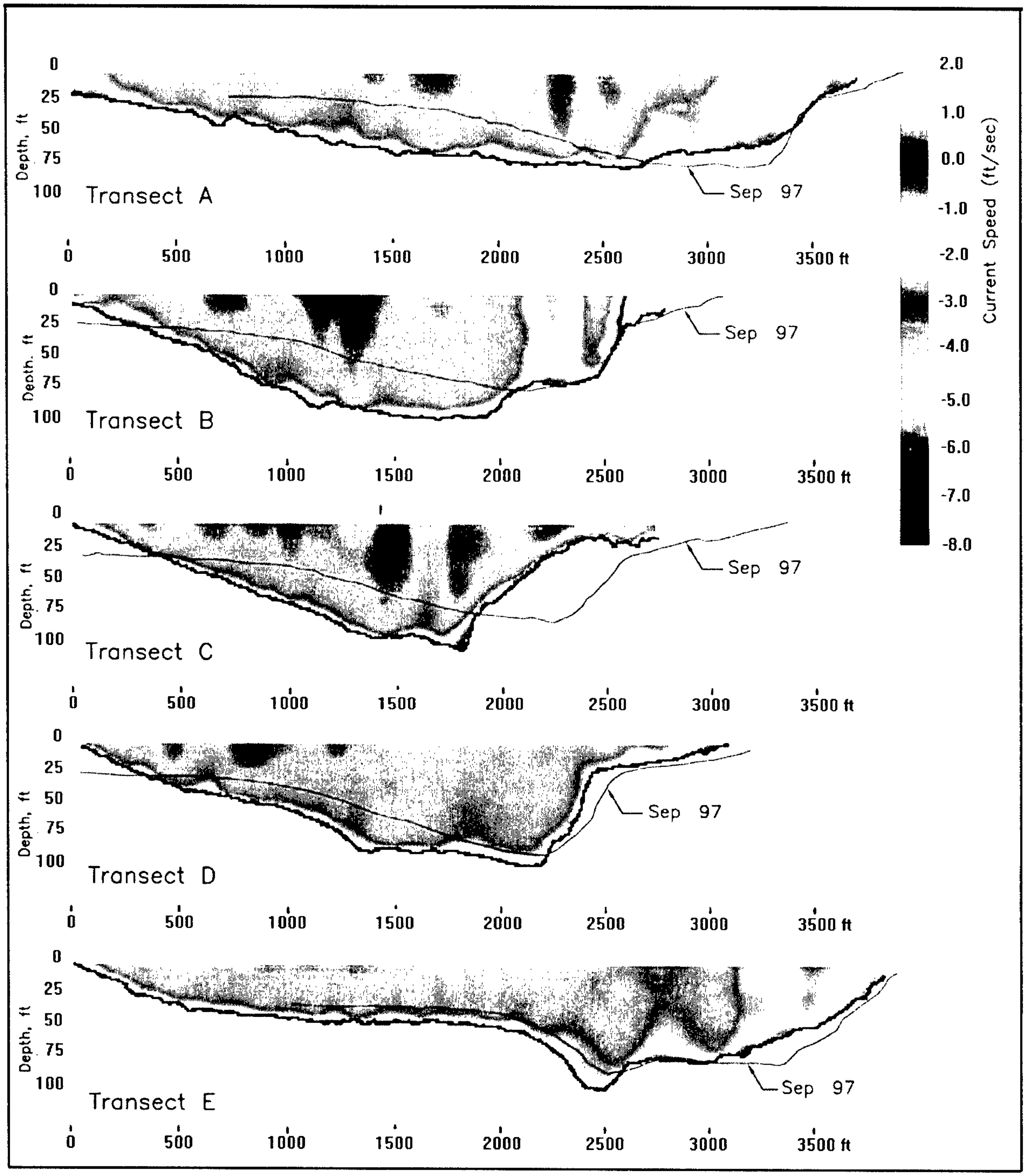


Figure 3-8. Along-channel ebb velocity pattern from ADP transects of 12 April 2000 aligned with channel depth profiles of 3 September 1997

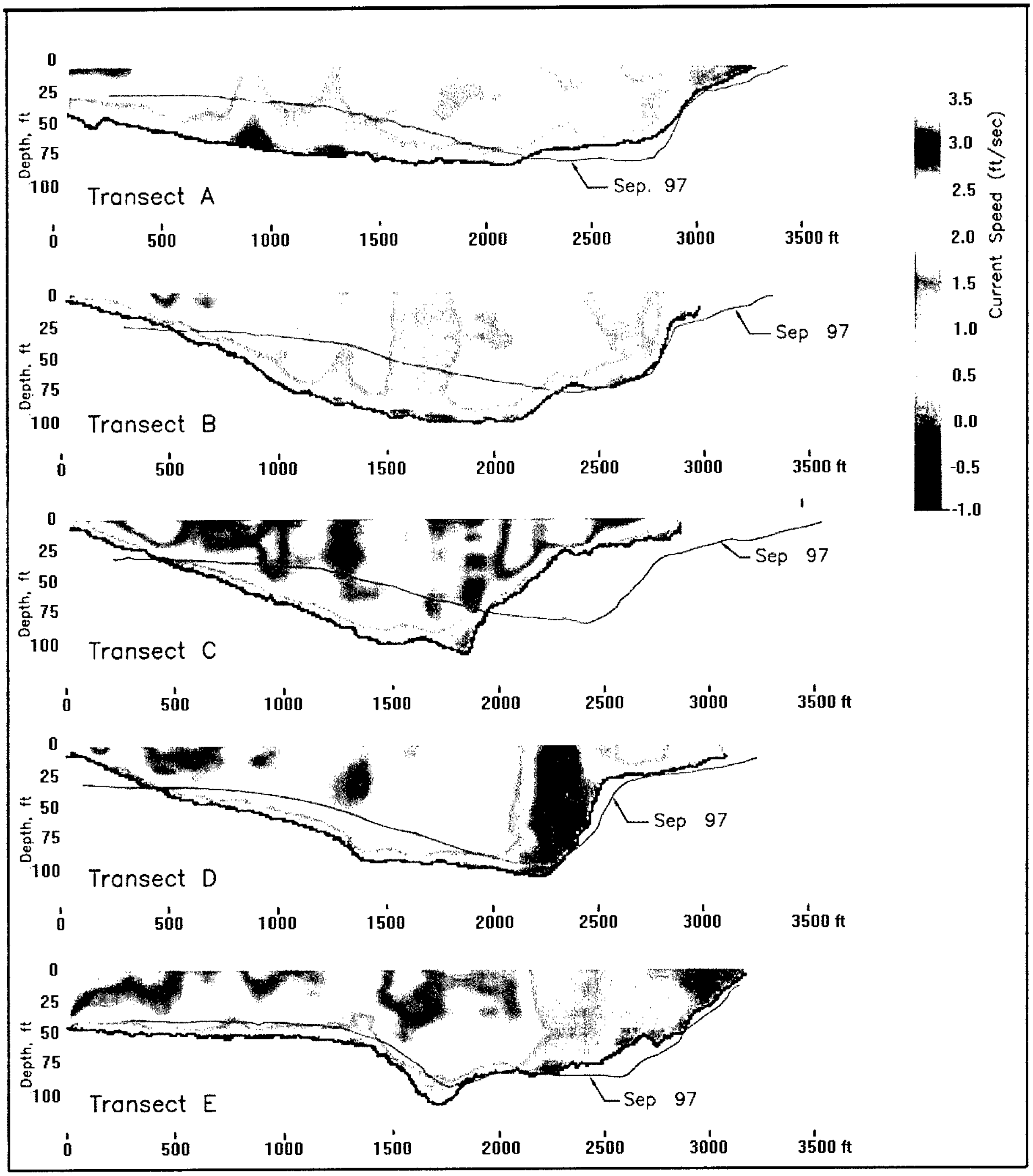


Figure 3-9. Along-channel flood velocity pattern from ADP transects of 12 April 2000 with channel bathymetry measurements of 3 September 1997

Bar and Entrance Channel Bathymetry Change

The bathymetry data obtained in August 1998, April 1999, October 1999, May 2000, September 2000, and March 2001 were analyzed for the following information:

a. Channel alignment relative to channel alternatives recommended Report 1.

b. Initial dredging volume.

c. Stability of position over time.

d. Long-term dredging requirement.

The fit of the natural channel alignment to the alternative designs is indicated with data from the individual bathymetric surveys from August 1998 through March 2001 and depicted graphically in Figures 3-1 through 3-6. The survey sequence demonstrates that the natural channel, although well aligned with Alternative 3A, experienced some shoaling in the 3A alignment, and the depths slightly improved (increased) for the inner portion of the 3H alignment. By 1999, the deepwater channel had formed an S-curve in the entrance. In analysis for 2000 and 2001, Alternative 3B, which is specified to follow the naturally formed alignment of deep water in the North Channel and across the bar, was changed from the southern position it occupied in 1999. In 2000, the 3B channel alignment was fit to the May 2000 bathymetry using specifications of 500-ft widths in straight reaches and 1,500-ft widths in turns.

Comparing channel design templates with bathymetry measured on the six dates since 1998 provided measures of initial dredging volumes required to achieve each channel design at specific times. Each alternative channel was divided into Reaches A, B, and C (Figure 3-10) to better quantify the variability of the fit of the alternative channels to observed bathymetry. Dredging templates include the allowable 2 ft of overdepth dredging, to a total channel depth of 28 ft. Computed initial dredging volumes corresponding to each alternative design are listed by date and reach in Table 3-1. The table shows that volumes for Alternative 3B over the period of the six surveys are extremely variable, increasing from 0.2 to 1.6 million cu yd in 1 year, then decreasing to 0.2 million cu yd again the next year. The large volume for Reach B in 1999 demonstrates the extent of shoaling of the S-shaped curve as the natural channel shifted to a northerly location in 1999-2000.

Alternative 3A, however, showed a volume decrease in Reach B and in the total channel in that period of channel shifting, but larger volumes at other times. The volume average for the monitoring period (0.5 million cu yd) is slightly less than that of Alternative 3B (0.6 million cu yd).

Alternative 3H shows a generally declining trend in initial dredging volumes through the monitoring period. The average volume (1.4 million cu yd) is significantly greater than those of 3A or 3B. The trend in volumes from 1998 to 1999 gave some indication that the natural deepwater channel could develop along the 3H alignment. The progressive shift of depth contours northwestward from the SR-105 dike after 1999 (Figures 3-4 through 3-6) does not support a projection that Alternative 3H will have a significantly smaller initial dredging volume at some future time.

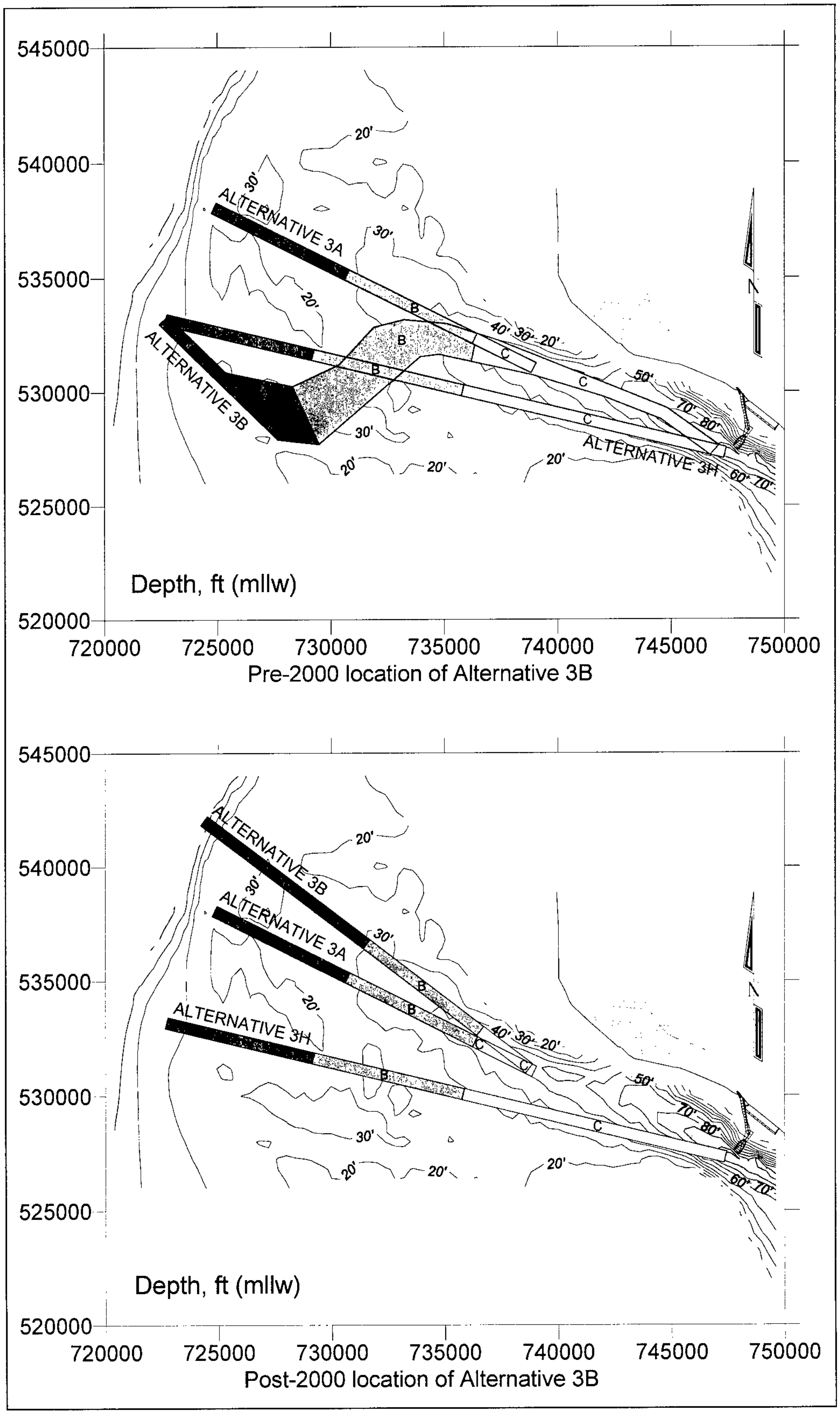


Figure 3-10. Reaches of Alternative Channels 3A, 3B, and 3H for comparing initial dredging volumes

Table 3-1
Volumes Within Selected Channel Templates

Date	Reach A	Reach B	Reach C	Total
Alternative 3A Volumes (million cu yd)				
8/31/1998	0.72	0.13	0.00	0.84
4/29/1999	0.21	0.00	0.00	0.21
10/21/1999	0.16	0.00	0.00	0.16
5/16/2000	0.45	0.02	0.00	0.47
9/28/2000	0.61	0.01	0.00	0.62
3/6/2001	0.79	0.02	0.00	0.81
Alternative 3B Volumes (million cu yd)				
8/31/1998	0.00	0.19	0.00	0.19
4/29/1999	0.31	0.68	0.00	0.99
10/21/1999	0.07	1.53	0.00	1.60
5/16/2000	0.05*	0.00*	0.00*	0.05*
9/28/2000	0.21*	0.00*	0.00*	0.21*
3/6/2001	0.44*	0.01*	0.00*	0.45*
Alternative 3H Volumes (million cu yd)				
8/31/1998	0.73	0.44	1.07	2.20
4/29/1999	0.37	0.60	0.36	1.31
10/21/1999	0.45	0.86	0.21	1.51
5/16/2000	0.25	0.66	0.03	0.93
9/28/2000	0.32	0.82	0.01	1.13
3/6/2001	N/A**	N/A**	N/A**	N/A**

*Alternative 3B changed alignment in 2000, according to channel design criteria
**Area of survey insufficient to report channel volume

Stability of channel position

Bathymetric comparisons were made with the August 1998 survey as the base between surveys of April 1999 (Figure 3-11), October 1999 (Figure 3-12), May 2000 (Figure 3-13), September 2000 (Figure 3-14), and March 2001 (Figure 3-15). The figures show the areas of deposition and erosion. Areas of positive elevation change shown in the figures indicate depth became less (deposition occurred) during the period from the earlier date to the later date noted on each figure. Conversely, negative elevation changes indicate erosion occurred between the two dates. Deposition occurred at locations along the North Cove shoreline, at the northeastern part of Deadman Island, at the location of the S-curve over the bar, and at the seaward edge of the bar.

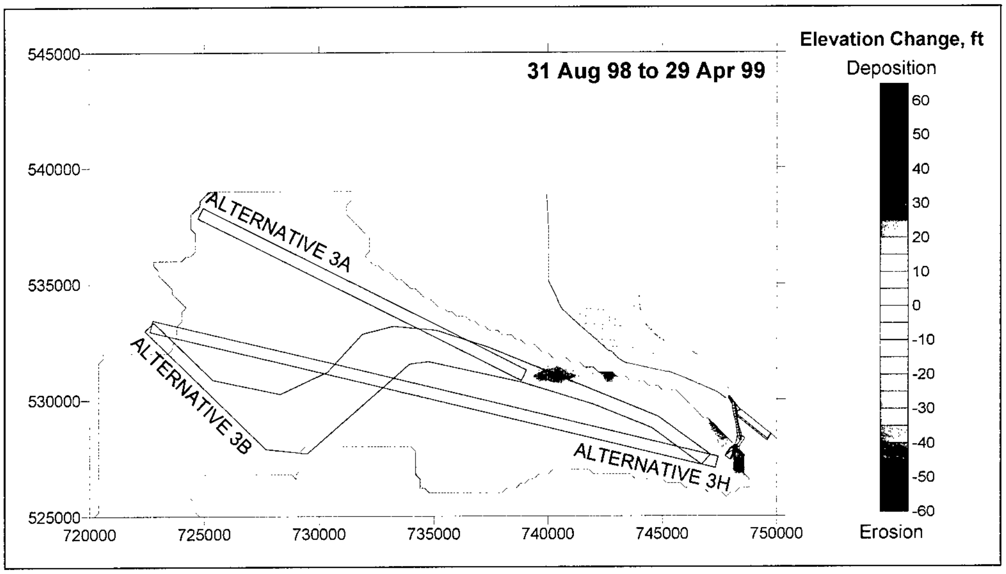


Figure 3-11. North Channel bathymetry change, August 1998 to April 1999

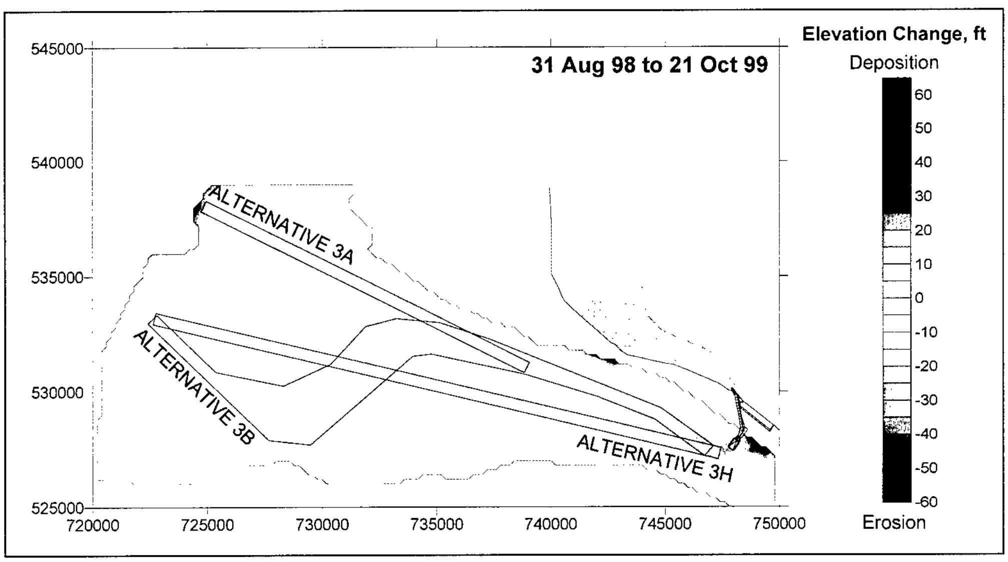


Figure 3-12. North Channel bathymetry change, August 1998 to October 1999

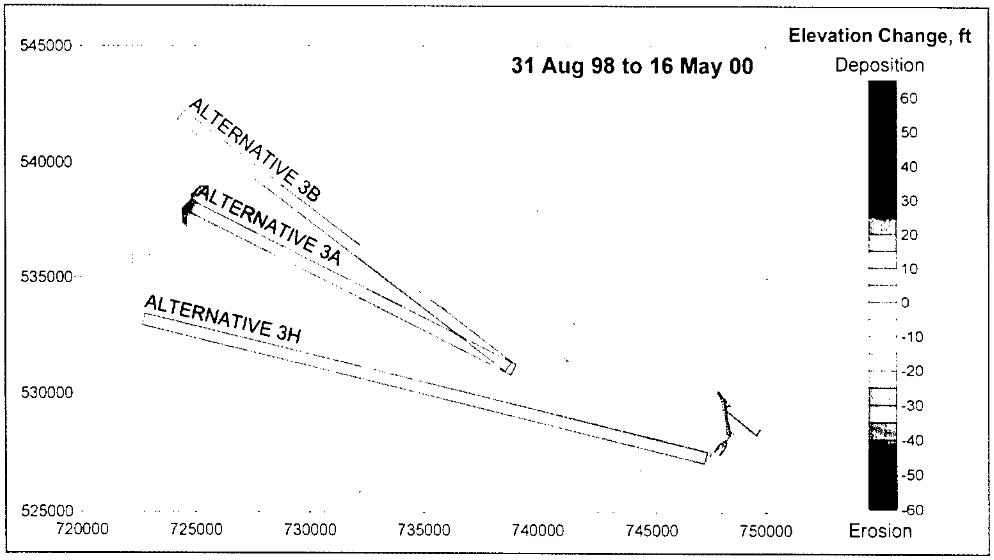


Figure 3-13. North Channel bathymetry change, August 1998 to May 2000

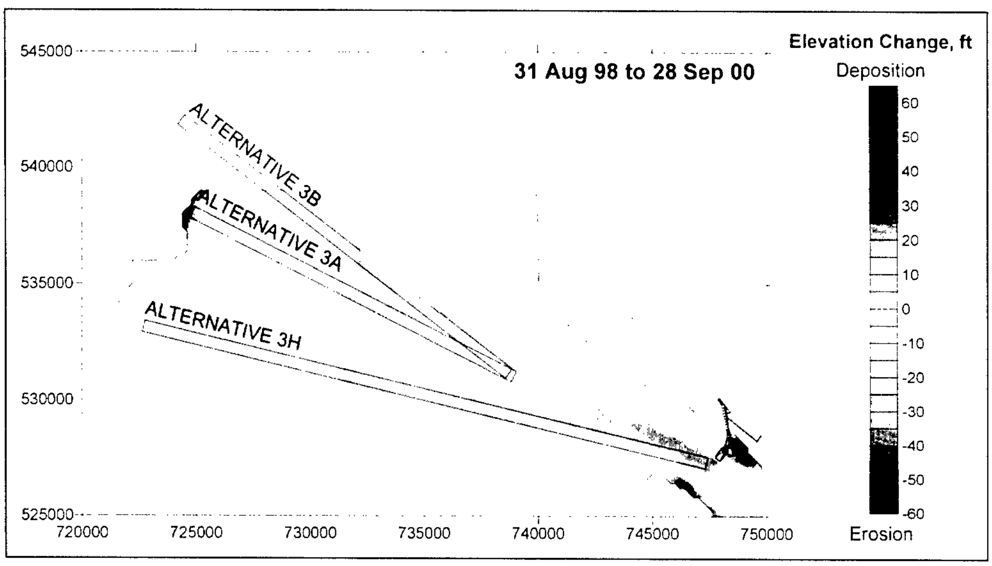


Figure 3-14. North Channel bathymetry change, August 1998 to September 2000

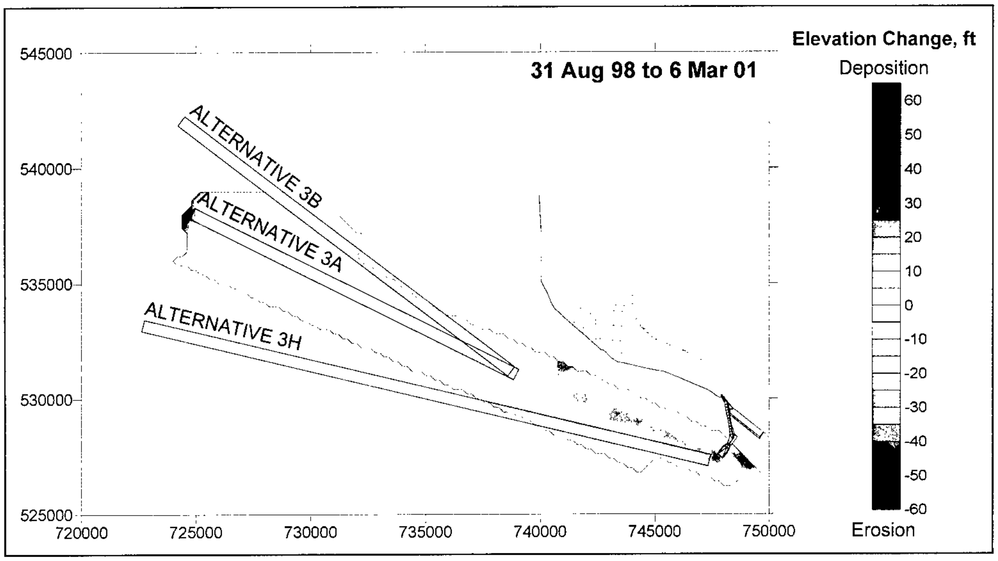


Figure 3-15. North Channel bathymetry change, August 1998 to March 2001

Long-term dredging requirement

Report 1 estimated lifetime shoaling loads for eight different channel alternatives. A geometric form, or channel template, was created to match channel design cross sections (in width, depth, and side slopes) and alignment. One or more templates were positioned for each channel alternative. Annualizing the volume differences between the 1998 and 1999 surveys within each channel template produced typical shoaling rate estimates for each alternative. The 1998 and 1999 bathymetries were based on the most accurate surveys available, but they represent only a single year. Therefore, volume differences were also calculated for 32 previous years, and interval estimates (±1 standard deviation) were adopted as predictors of future shoaling rates for each alternative.

The methods applied in Report 1 yielded results that initially narrowed the number of preferred alternatives to four: three in the North Channel and one in the Middle Channel. New dredging estimates were to be calculated with the latest (or possibly even a projected) bathymetry prior to construction. Now, it appears additional updates will be necessary. Bathymetry surveys in 2000 and 2001 revealed lower rates of shore erosion and northward channel migration at North Cove, and even a reversal of long-term trend in channel movement in the vicinity of the SR-105 dike. The dike might have lengthened the number of years over which Alternative 3B would remain within prescribed, safe curvatures. Two to 5 more years of observation are required to determine if the period between realignments is lengthening or if other channel migration patterns are changing. At present, the North Channel is anchored near the underwater tip of the dike. The length of stabilized channel may be increasing by extension westward. Long-term dredging estimates could decrease significantly if shore erosion rates drop and/or if the length of channel stabilized by the SR-105 dike grows. There is no indication of increased shoaling in the inner reach of the North Channel.

Interpretation of Bathymetry

In previous geomorphologic cycles, formation of a new channel through the location of the spit dissection has been associated with faster-than-average northward migration of the North Channel, as well as accelerated erosion of the North Cove. In 1999 and 2000, the new northern channel formed where the spit was dissected, but the presence of the underwater dike at the SR-105 project area appears to have hindered northward movement of the North Channel in the vicinity of North Cove. In fact, the thalweg has moved 500 to 1,500 ft southward in the vicinity of the underwater dike. This indicates an interruption of the rapid northward shifting that would probably have occurred without the SR-105 project influence. Less sediment entered the entrance and bar channel, because of less erosion along North Cove. The rate of sediment feeding the entrance and bar channel is thought to be at least partly responsible for the dynamics of Deadman Island. If the interruption of North Cove erosion is long term, it is expected to have a restricting influence on the range of north-south migration of the bar channel in the future.

The Willapa Bay bar and entrance area was divided into outer and inner parts along the E735000 state plane coordinate to interpret bathymetric change. The outer part of the channel contains Reaches A and B, and the inner part Reach C, each analyzed in the "Initial Dredging Volume" section.

The outer part of the entrance experienced bottom change of 20 ft of erosion at some locations and 20 ft of deposition at other locations between 1998 and 2001. The general pattern of change consisted of filling along the S-shaped turn and deepening in a more northerly alignment. The random aspect of bottom change in the outer bar (Figures 3-11 through 3-15) dominates its morphodynamic expression in the relatively short period of 1998 through 2001.

The inner part of the entrance is distinguished by progressive changes in depth related to the SR-105 project, completed in October 1998. Preconstruction bottom depths can be approximated by the survey of 21 August 1998. The survey of 29 April 1999 indicated that the groin and dike on the north side of the North Channel deflected tidal flow toward the south, scouring a new channel thalweg position (Figures 3-7 and 3-9). The survey of 21 October 1999 indicated that the process of scouring a new channel position continued and extended west-northwestward. Surveys of 16 May 2000 and 29 September 2000 show that channel deepening continued at locations south of the project, and toward the west-northwest direction, approximately 5,000 ft from the project.

The observed channel deepening in the vicinity of the SR-105 project shows no signs of halting. Deepening is inferred to be caused by increases in peak tidal currents due to the presence of the SR-105 dike. The adjustments may continue for several more years. Because they appear to be in response to the SR-105 project, the new channel location is assumed to be more stable than the pre-project location.

Comparison of trends in bottom change along three channel alternatives reveals the following:

a. Deepening and shifting of the thalweg occurs along the alignment of channel Alternative 3A and is less noticeable along the Alternative 3H

alignment. Depth changes for Alternative 3A are more aligned with the channel axis, but do not extend the full distance from the dike to deep water outside the bar.

b. Depth is increasing for Alternative 3H as the inner part of the entrance channel migrates southward away from North Cove. It cannot be concluded at this time whether bottom changes along channel Alternative 3H will ultimately result in smaller initial dredging volume than is indicated for Alternative 3A.

The central questions are: how far to the west will these changes extend, and what part of the channel will be stabilized by the SR-105 project? The answer to these questions will depend upon findings from a long-term monitoring program.

Bathymetry of October 1999 and September 2000 are compared in Figure 3-16, which minimizes seasonal variation in morphology. Changes between those surveys indicate that the Willapa North Channel is expanding the northwest outlet, which began opening during the 1997 El Niño (Hands 2000), through the shoal area extending southward from Cape Shoalwater. South of the area where the channel is enlarging, a deposit more than 12 ft thick has accumulated where the channel had been forced southward around the end of the shoal. The former position of the S-shaped channel, now cut off from most of the flow, is filling with sand, apparently coming from all directions. A lens of accretion appeared seaward of the 28-ft depth contour, just as a similar lobe accreted in the past where sediment was jetted seaward. The channel inside the entrance of the North Cove area has cut deeper as the portion of the south bank shallower than 20 ft migrated northward. The north bank has not moved northward a corresponding amount, resulting in a narrower, deeper channel at North Cove.

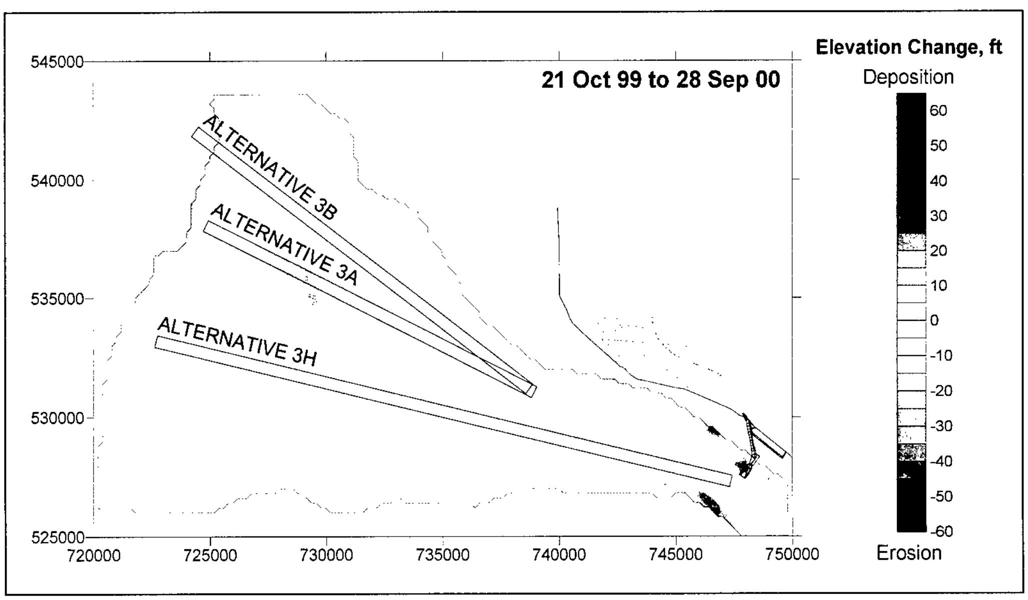


Figure 3-16. North Channel bathymetry change, October 1999 and September 2000

The bathymetric survey performed for the SR-105 monitoring on 8 April 2000 showed that the deepest part of the scour hole located directly northwest of the dike was 127 ft deep, and the maximum depth recorded at the scour hole southwest of the dike was 109 ft. The north bank shows net deposition, whereas the south bank generally shows net erosion (refer to cross-section plots in Figure 3-7). Profile comparison at all five transects show a generally deeper thalweg in May 2001 than in the pre-project September 1997 survey, as well as a southward movement of the thalweg. Prior to constructing the dike, the southern edge of the channel in this location contained a broad shelf between 20 ft and 30 ft deep. Figure 3-7 shows that the south side of the channel below 40 ft of depth was eroded after dike construction. Some accretion can also be seen on the north side of the channel. Transects B, C, and D, centered around the dike, indicate that the former shelf area became filled to a depth shallower than 20 ft, resulting in an overall steepening of the south bank after dike construction.

Depth profile comparisons between 1997 and 2000 (Figure 3-7), show that the north shore of Deadman Island is migrating northward into the North Channel, and the eastern end is eroding westward. The shoreline of Deadman Island, which forms a boundary of the North Channel, cannot be identified from available surveys; trends of movement are continuing. The channel seaward of the dike appears to be shifting southward. The intensity of scour and qualitative interpretation of ADCIRC results indicate that hydrodynamic changes caused by the construction of the dike could cause continuing adjustment of the bathymetry (Militello 2002). The channel seaward of the dike appears to be shifting southward in response to the dike. Depending on the extent of the influence of the dike, the period of adjustment is expected to continue for years.

Fill volumes within the templates of the alternative channel designs calculated with bathymetry of 1998 through 2001 are listed in Table 3-1. The trend of the volumes through time indicates that Alternative 3A more closely fits the natural bathymetry in 1999 than in 1998. From 1999 to 2000, however, the volume inside the 3A template increased greatly. Alternative 3B showed a large increase in volume within the template as the S-curve began to be abandoned between 1998 and 1999. Because Alternative 3B is an alignment that follows the natural deep water, the 3B template was relocated for the 2000 bathymetry (Figure 3-10). Volumes listed for 3B after 1999 in Table 3-1 correspond to the dredging that would be required to construct the project in the relocated template. Alternative 3H shows a trend of declining volumes from 1998 to 2000.

The ADP transects of October 2000 indicate that current perpendicular to the section has a maximum at the deepest part of the channel. Comparison of channel cross-section profiles between 1997 and 2000 shows that the greatest depth increase has occurred where the velocity is the greatest, and accretion has occurred near the north bank where the velocity is less than 2 ft/sec. This pattern of scour, deposition, and velocity magnitudes indicates that the underwater dike modifies the hydrodynamics within a certain zone of influence along shore, and that the bottom is responding to the flow modification within that zone. The dike and groin deflect current away from the North Cove shore, and the deepest part of the profile has shifted southward since construction of the dike. By comparing the bathymetry changes and noting the velocity pattern at each of the five measured sections, it is apparent that the channel in the vicinity of the dike has

presently halted its northward migration during the monitoring period. Examining depth contours by date (Figures 3-1 through 3-6) shows that channel deepening, in a region located generally south of the pre-project thalweg, is extending in both the ebb and flood directions from the dike over time.

An optimal navigation channel design can be selected on the basis of economics of initial dredging and long-term maintenance dredging. Costs are projected with greater certainty if two characteristics are consistently observed. The first is self-stabilization of a channel at such a distance from North Cove as to minimize shore erosion at North Cove. The second is the westward extension of self-scouring channel depths greater than project depths. Continued monitoring is required to confirm those characteristics.

Bay Center Entrance Channel

Historical bathymetry

The Bay Center Entrance Channel consists of an approximately 1,000-ft wide natural channel of relatively stable alignment and varying depth. The major geomorphologic components of Bay Center Entrance Channel from Nahcotta Channel to the mouth of the Palix River are illustrated in Figure 3-17. The figure shows the system morphology in July 1992. The feature designated the Northwest Channel, which connects the main East-West Channel and the Nahcotta Channel, has historically experienced rapid infill and often causes navigation difficulty for boats using Bay Center Small-Boat Harbor, a component of the Federal navigation project.

The field portion of the Phase II study provided data for verifying and adding detail to the description of transport mechanics in the channel and its morphologic response. The field data collection program documented the waves, currents, sediment concentration, and bed level before dredging and as the channel responded to the dredging. Frequent bathymetric surveys were also made to monitor the effectiveness of the dredging design and to aid in inferring sources and mechanisms that shoal the channel.

Bay Center Entrance Channel is a prominent natural channel (Figure 3-17) appearing on the earliest aerial photographs and on hydrographic surveys from the beginning of the twentieth century. It conducts discharge from the Palix, Bone, and Niawiakum Rivers to Nahcotta Channel, as well as exchanges tidal flow between the tidal flats and marshes of Bay Center and Willapa Bay. Bay Center Entrance Channel refers to the approximately west-northwest channel located between the northern tip of Goose Point and Nahcotta Channel. This naming convention is intended to avoid confusion with Bay Center Channel, which is the project feature that connects Bay Center Marina with Palix River.

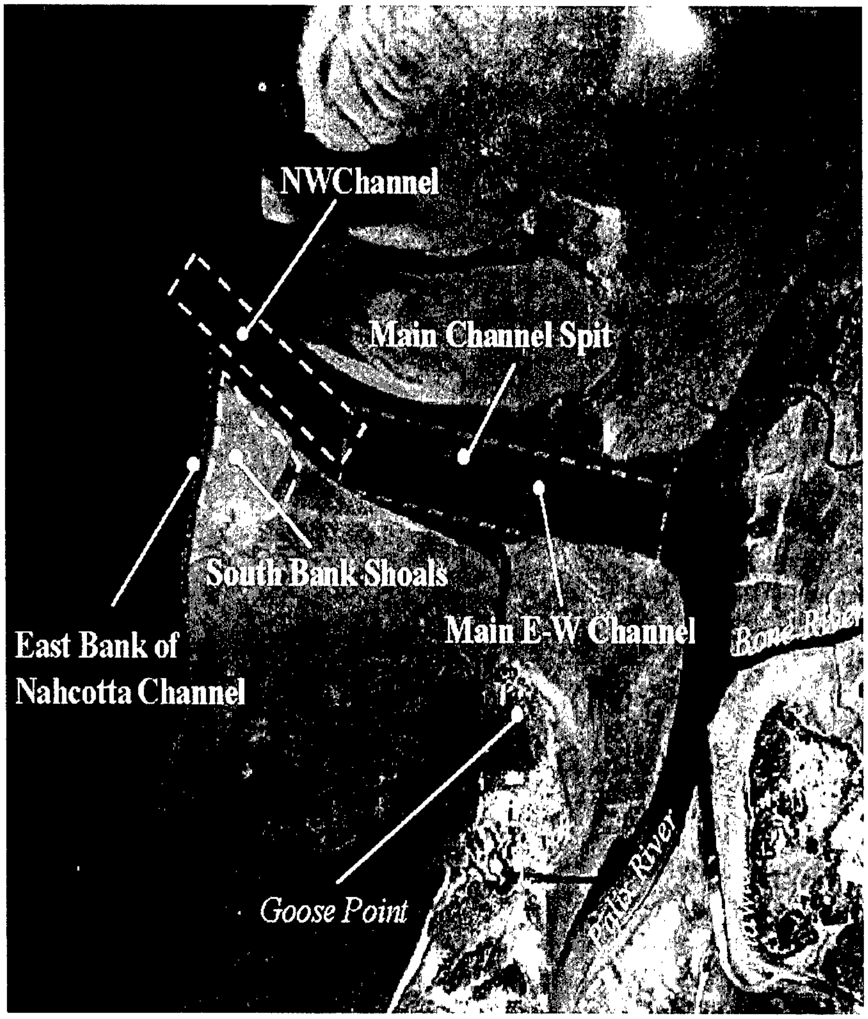


Figure 3-17. Bay Center Entrance Channel features, July 1992

The Seattle District performs maintenance dredging and regular bathymetry surveys in the Bay Center Entrance Channel. Figure 3-18 shows bathymetry of Bay Center Entrance Channel from 1939 through April 2000. The channel outline shown in the figures is fixed in location and was added to aid in comparing locations of deep water on the sequence of surveys. In the following surveys, elevations indicated with a positive number are above mllw. Maintenance dredging was again scheduled for the fall of 2000. Surveys between 1983 and 1999 were compared to analyze the channel behavior (PI Engineering 2000[1]) for recommendation of a dredging footprint for the scheduled maintenance dredging.

[1] Pacific International Engineering. (2000). "Bay Center Entrance Channel dredging preliminary recommendations." Technical Memorandum prepared for U.S. Army Engineer District, Seattle, WA, 11 pp.

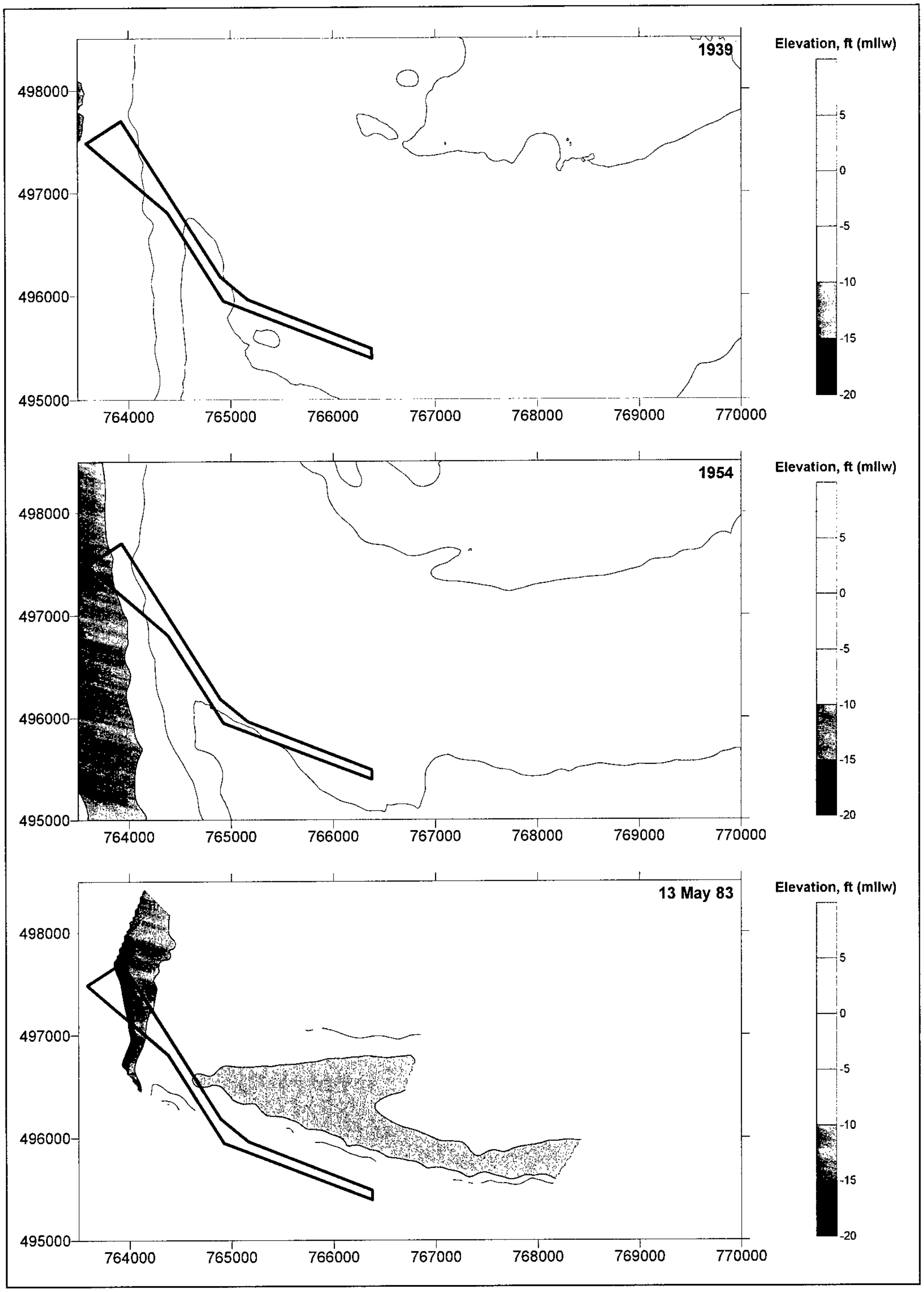


Figure 3-18. Historical bathymetry of Bay Center Entrance Channel (continued)

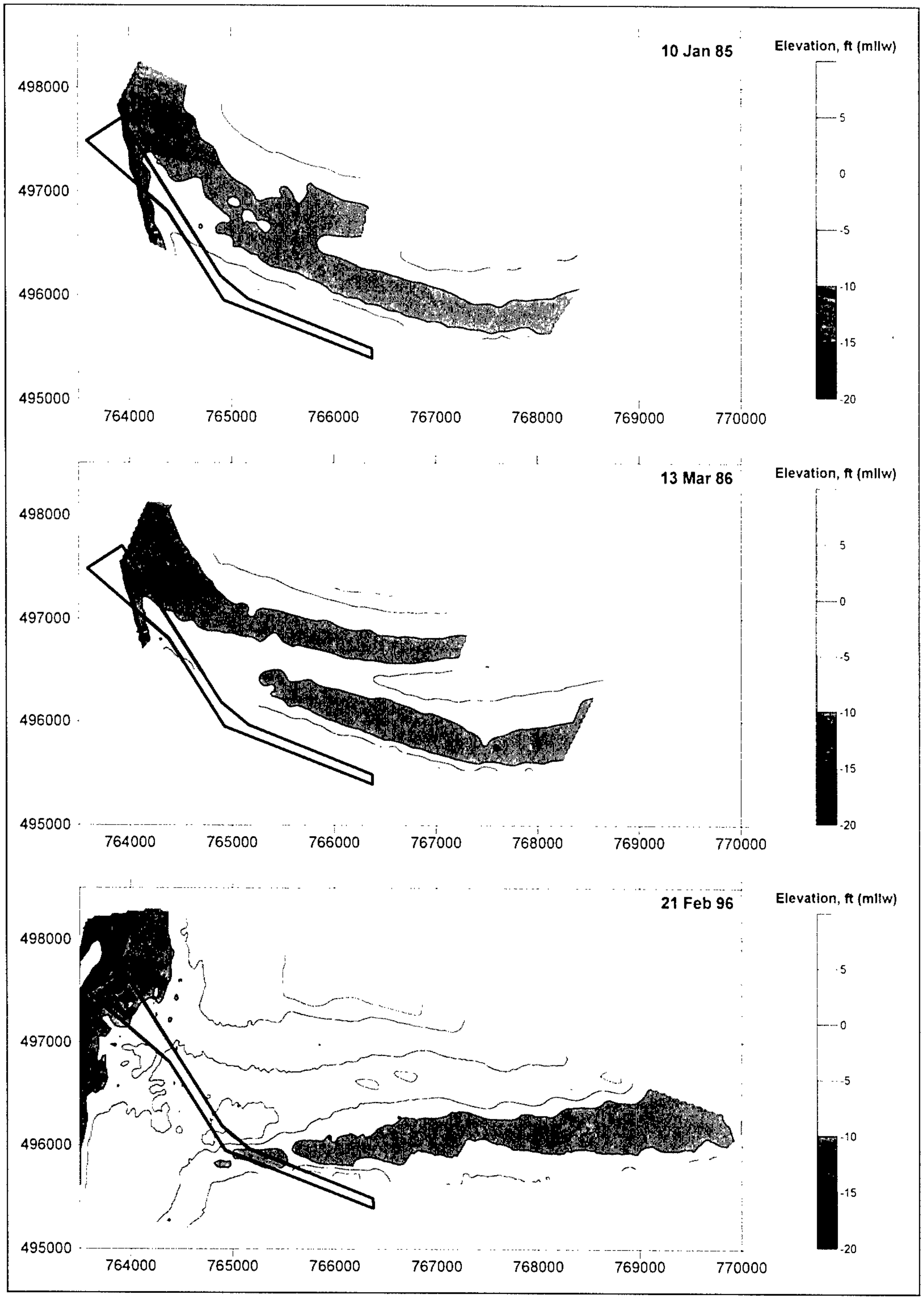


Figure 3-18. (Continued)

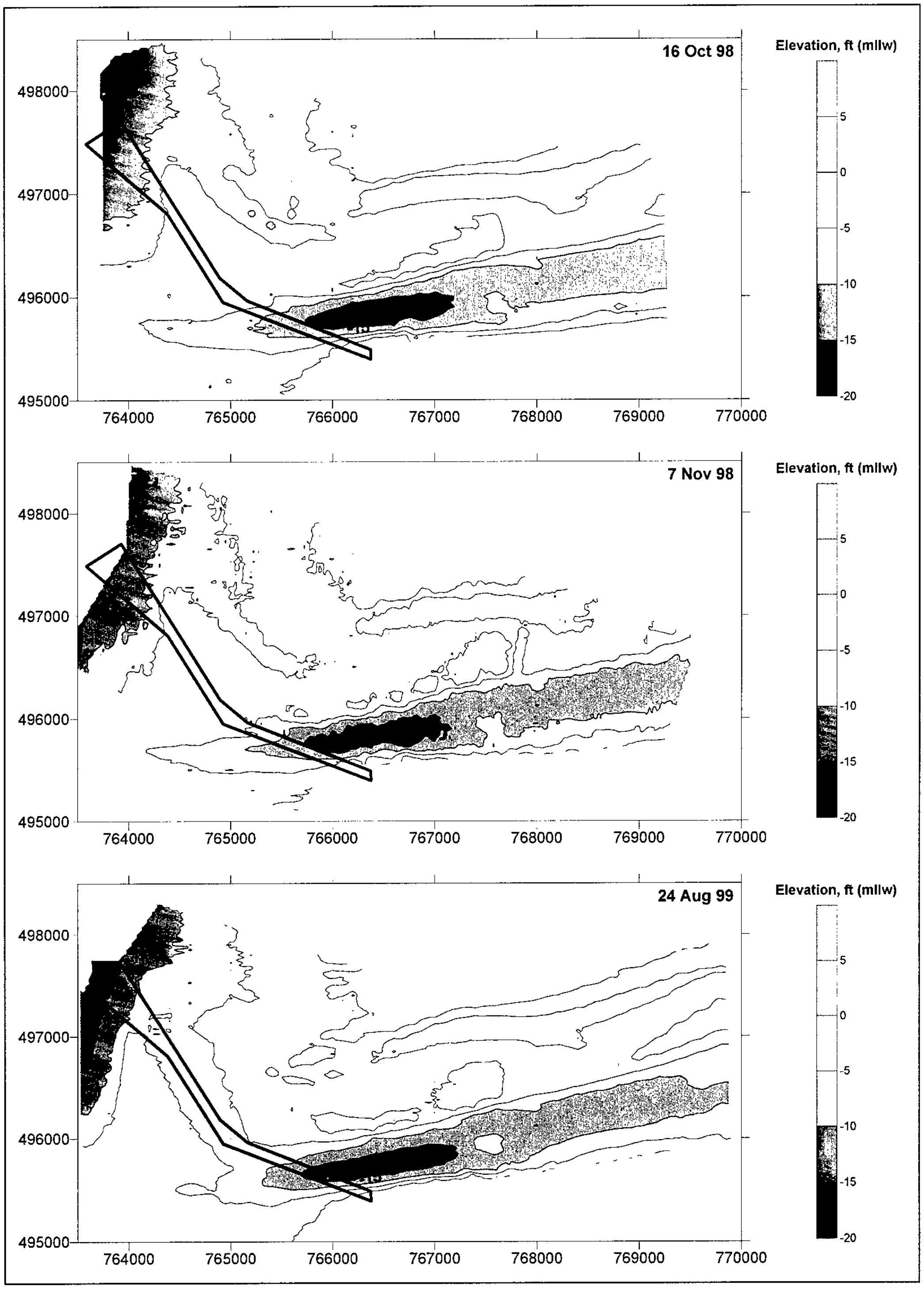


Figure 3-18. (Continued)

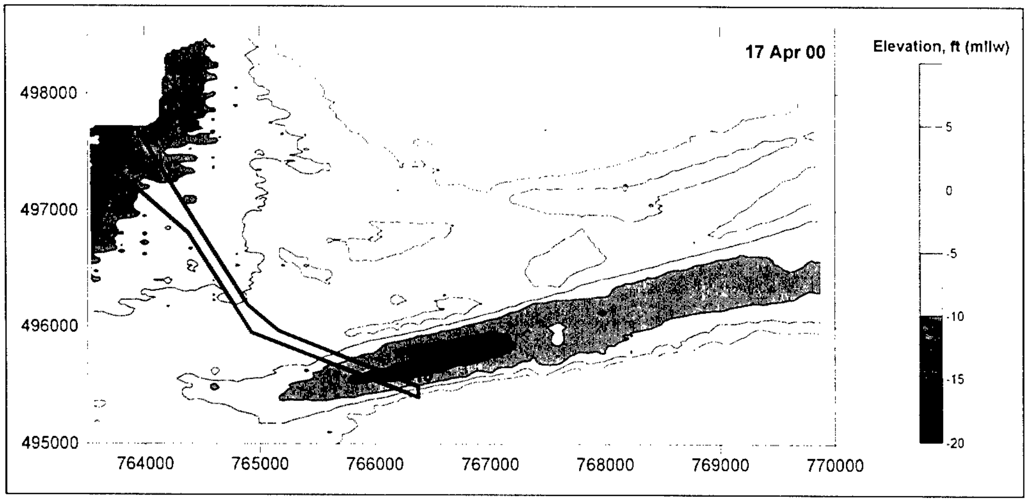


Figure 3-18. (Concluded)

The design of the dredging footprint was based on interpretation of directions and modes of sediment transport gained from analyzing of surveys and vertical aerial photographs. The survey dated 14 September 2000 (Figure 3-19) illustrates typical channel shoaling prior to dredging. At the time the dredging plan was developed, wave and current transport southward toward the north edge of the channel was thought to be the likely transport mechanism when the shoal area to the north is submerged. The aerial photograph in Figure 3-17 shows the shoal area exposed at low water. Observation of channel patterns suggested that a dredging footprint in the reach aligned northwesterly between the permanent deepwater portion of Bay Center Entrance Channel and Nahcotta Channel, with a flair at the northwestern end, would provide the most favorable controlling depth. The flair was introduced to accommodate anticipated deposition resulting from northward transport in Nahcotta Channel. The dredging footprint is overlaid on the depth contours in Figure 3-19. The estimated dredging volume to achieve a 15-ft depth in the footprint was more than 100,000 cu yd.

Dredging specifications were developed from the recommended footprint, and 178,000 cu yd of sediment were removed by clamshell dredge from 1 October 2000 through 7 November 2000. The dredged sediment was placed on split-hull barges and disposed near the Shoalwater Bay tribal property, within a 230-acre area, which is part of the designated Shoalwater open-water disposal area, near Buoy 13 in water depths between 5 and 20 ft. Monitoring of the disposal site consisted of hydrographic surveying from 3 October 2000 to 6 December 2000. Figures 3-20 through 3-26 show bathymetry of the Bay Center Entrance Channel surveyed by the Seattle District on 14 November 2000 (first postdredging survey), 29 November 2000, 20 December 2000, 6 January 2001, 8 February 2001, 8 March 2001, and 15 May 2001. The plotted survey of 14 November 2000 contains data collected in the dredged area on 7 November 2000 by the dredging contractor. The survey data were checked for datum and consistency and were found to be compatible with surveys made by the Seattle District.

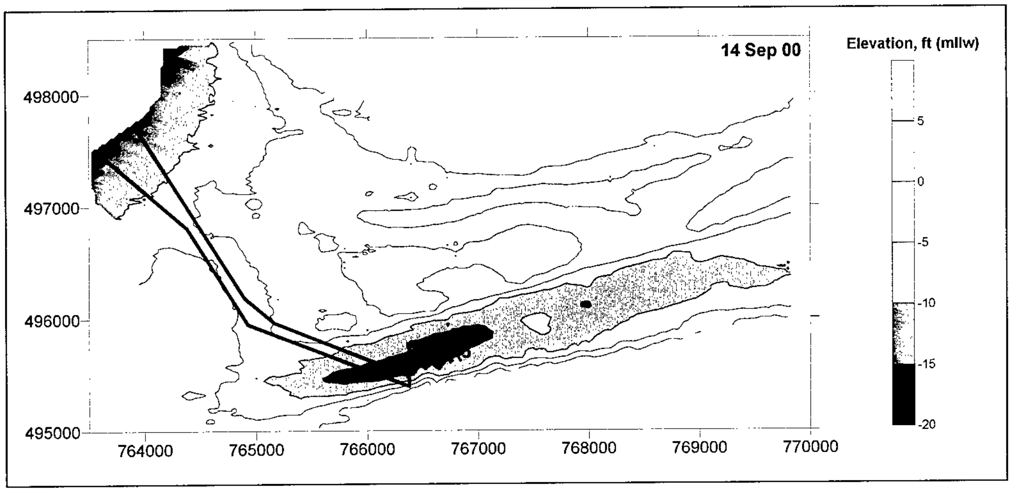


Figure 3-19. Bay Center Entrance Channel bathymetry with dredging footprint

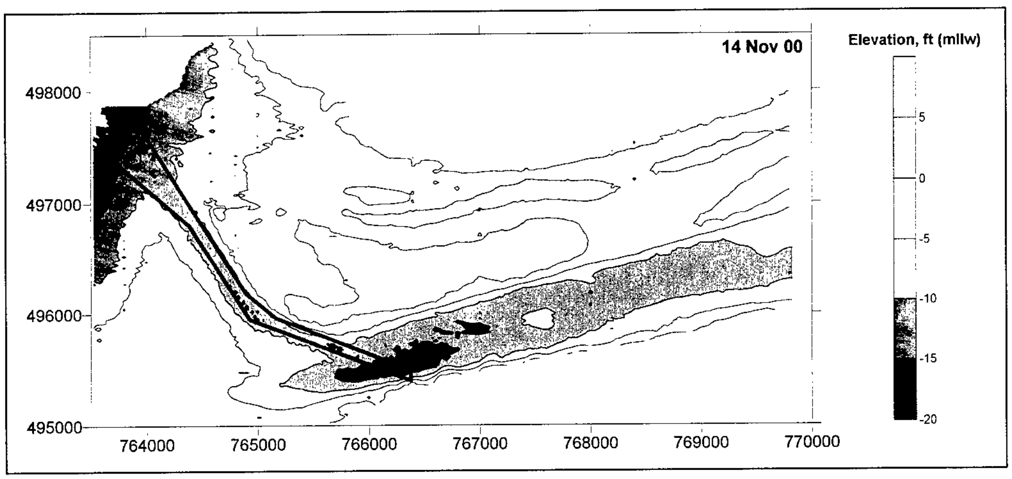


Figure 3-20. Bay Center Entrance Channel bathymetry, 14 November 2000

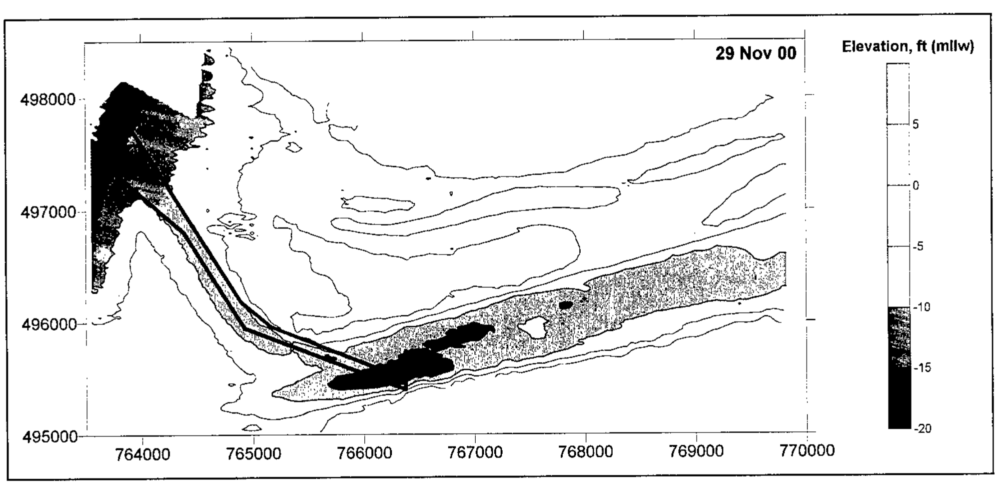


Figure 3-21. Bay Center Entrance Channel bathymetry, 29 November 2000

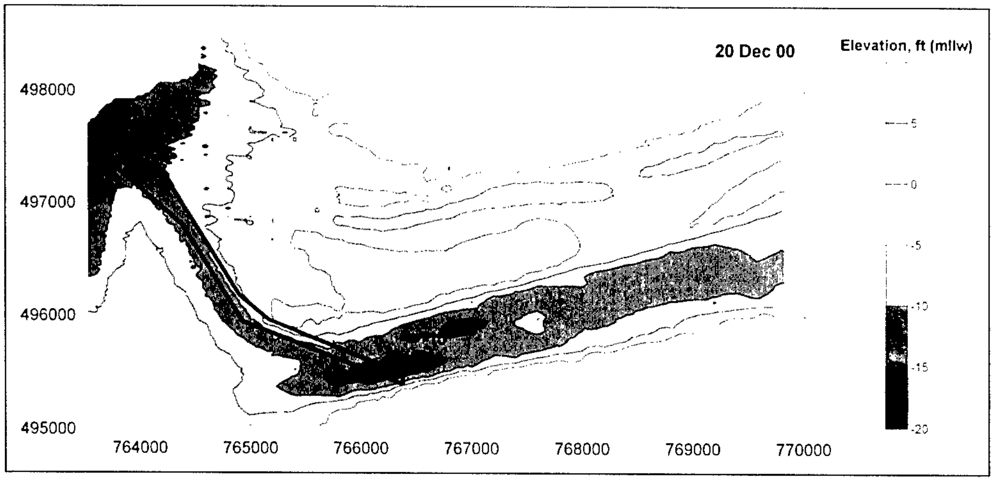


Figure 3-22. Bay Center Entrance Channel bathymetry, 20 December 2000

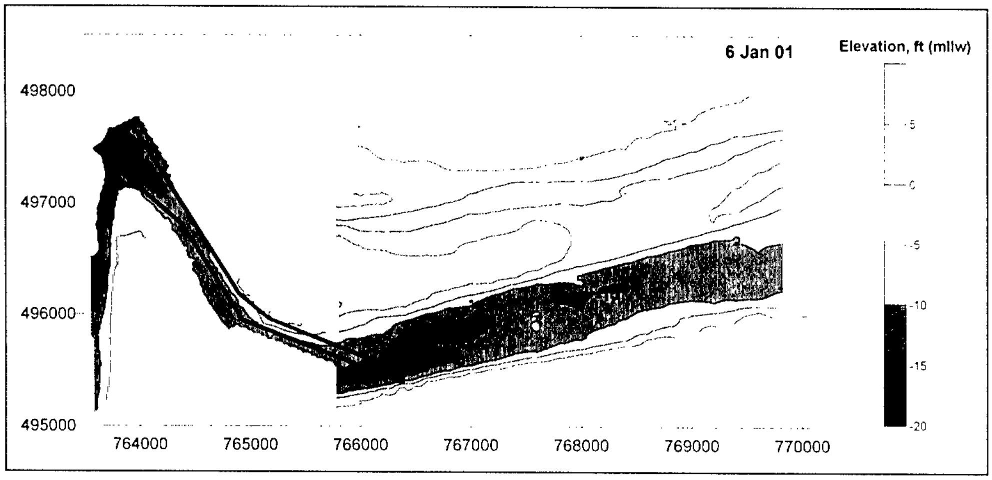


Figure 3-23. Bay Center Entrance Channel bathymetry, 6 January 2001

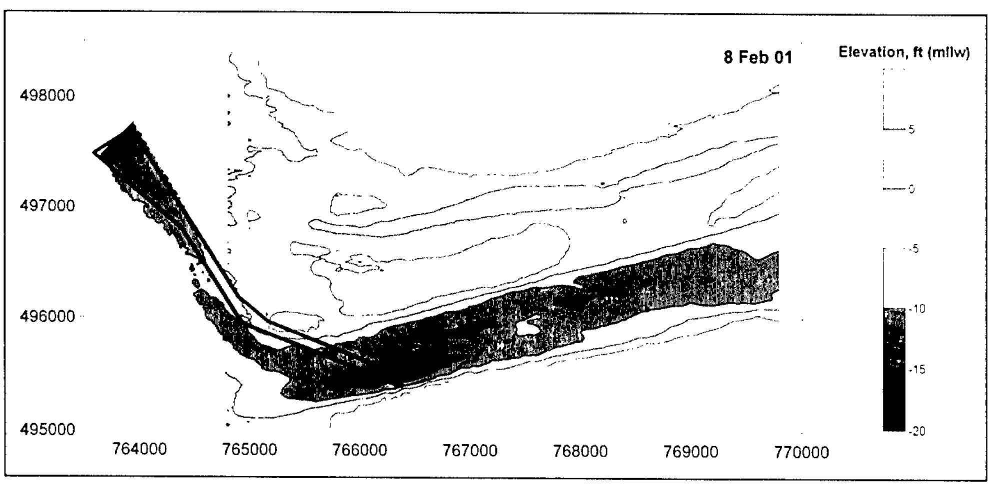


Figure 3-24. Bay Center Entrance Channel bathymetry, 8 February 2001

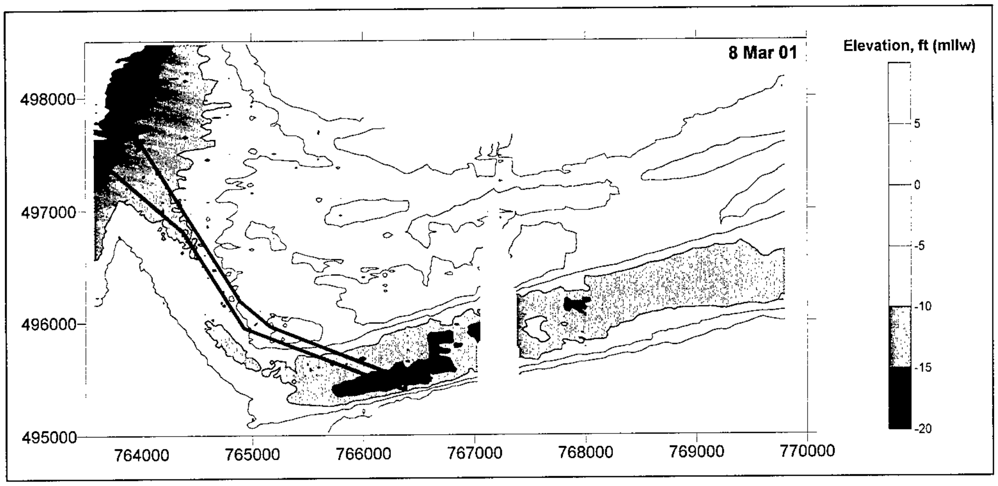


Figure 3-25. Bay Center Entrance Channel bathymetry, 8 March 2001

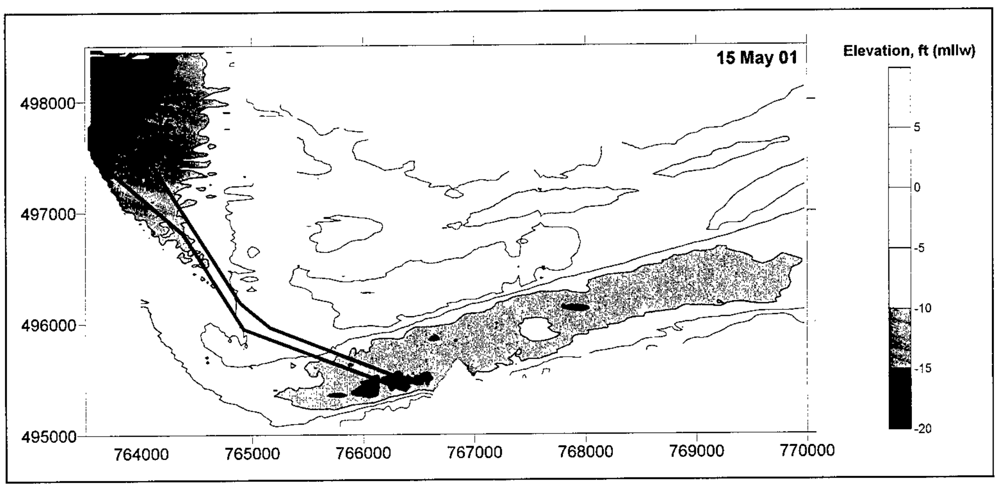


Figure 3-26. Bay Center Entrance Channel bathymetry, 15 May 2001

Bay Center Entrance Channel bathymetric change

Bathymetry change since the time of dredging in 2000 is described with the difference plots shown in Figures 2-27 to 3-32, which compare the bathymetry of 14 November 2000 with bathymetry following dredging by 15, 36, 53, 88, 110, and 170 days. No significant change in channel depth or position was observed in the main East-West Channel (refer to Figure 3-17 for location of channel features). The South Bank shoal appears to have increased in elevation approximately 3 ft between 29 November and 20 December 2000. Deposition is observed in the Northwest Channel, with maximum deposition occurring at the bend where the main East-West and North Channels connect. No occurrence of significant deposition is apparent at the mouth of the Northwest Channel.

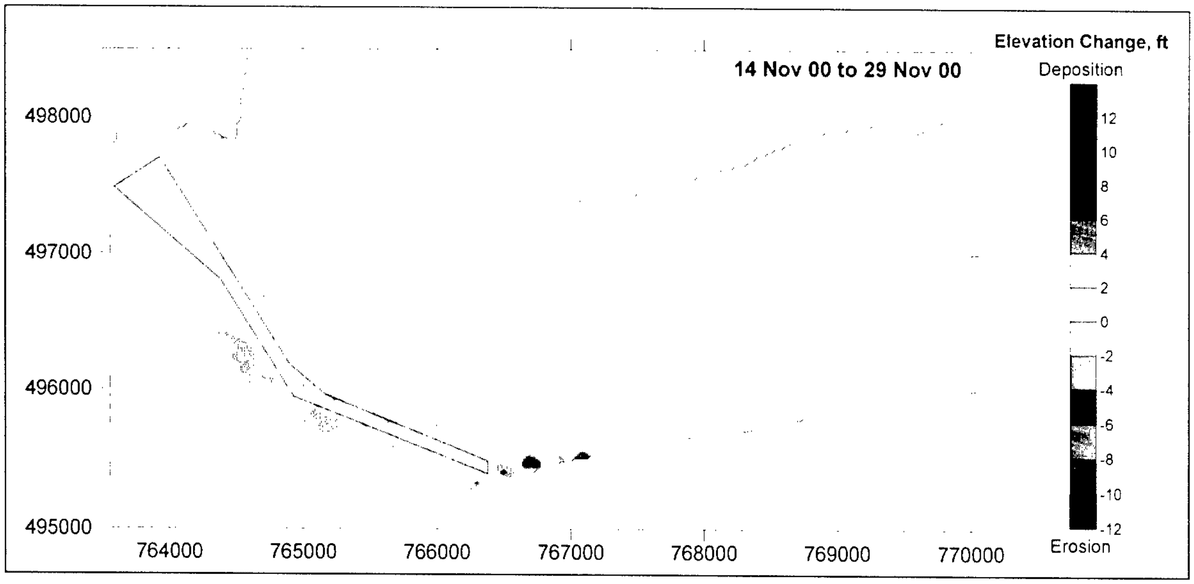


Figure 3-27. Bay Center Entrance Channel cumulative bottom change, 14 November 2000 to 29 November 2000

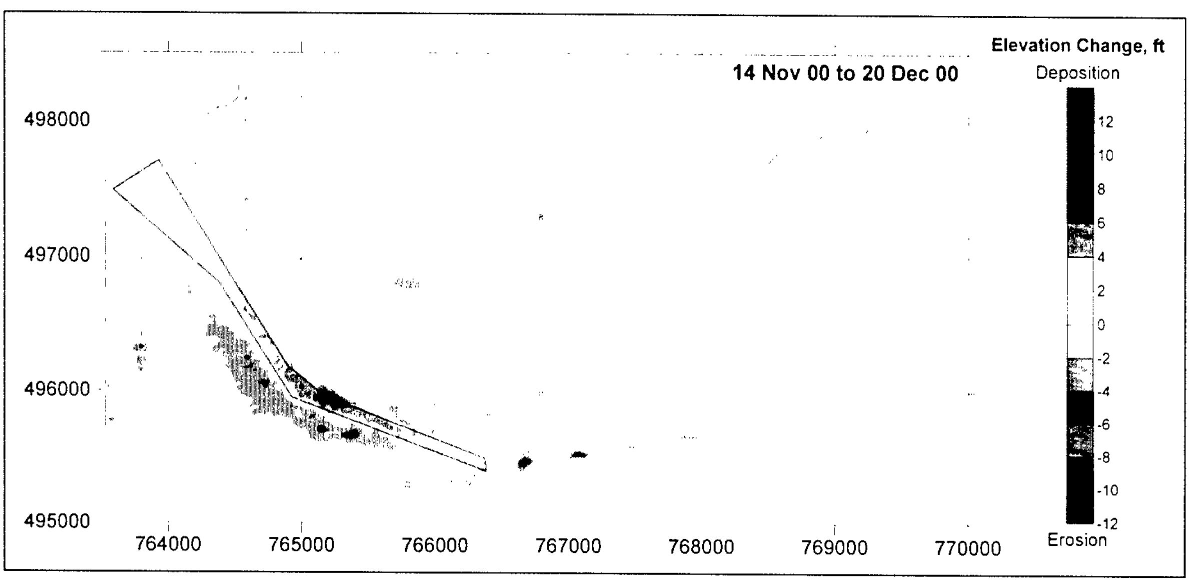


Figure 3-28. Bay Center Entrance Channel cumulative bottom change, 14 November 2000 to 20 December 2000

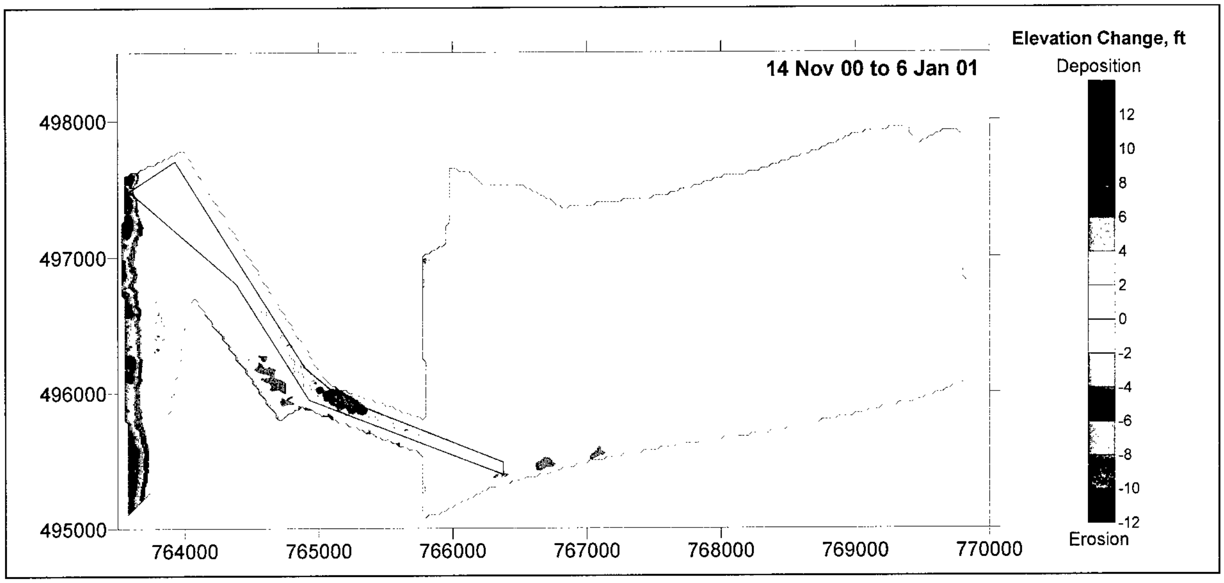


Figure 3-29. Bay Center Entrance Channel cumulative bottom change, 14 November 2000 to 6 January 2001

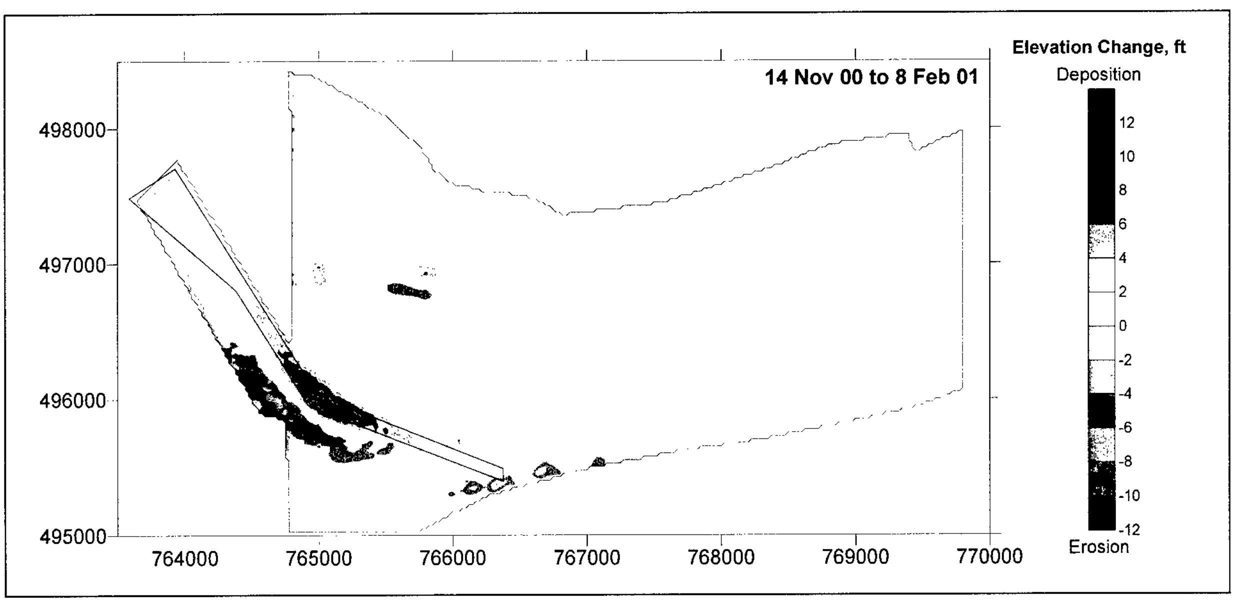


Figure 3-30. Bay Center Entrance Channel cumulative bottom change, 14 November 2000 to 8 February 2001

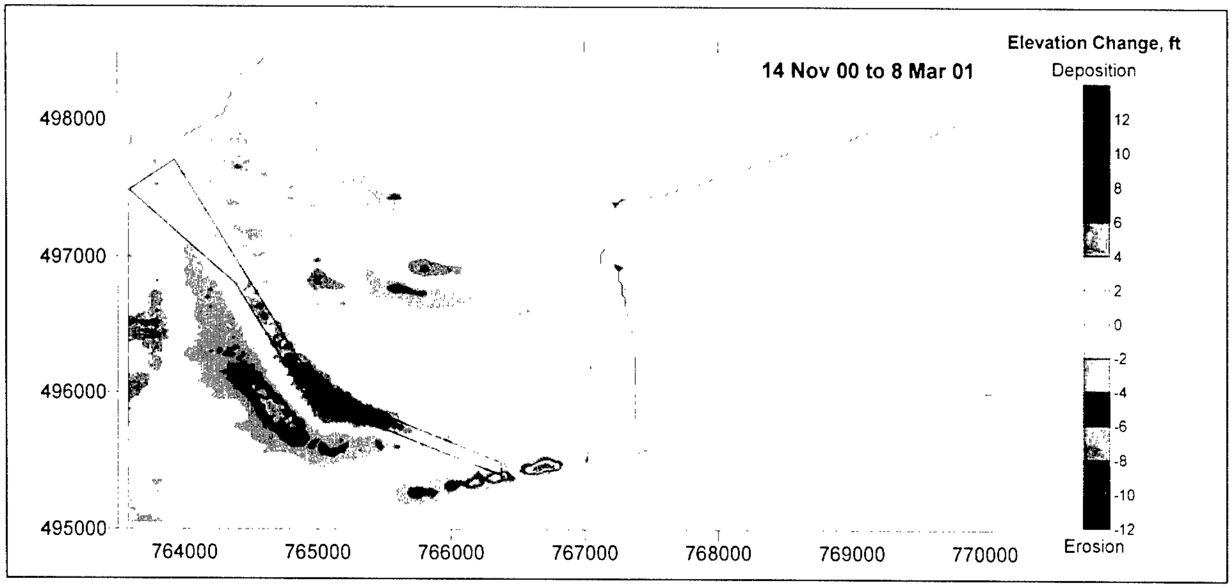


Figure 3-31. Bay Center Entrance Channel cumulative bottom change, 14 November 2000 to 8 March 2001

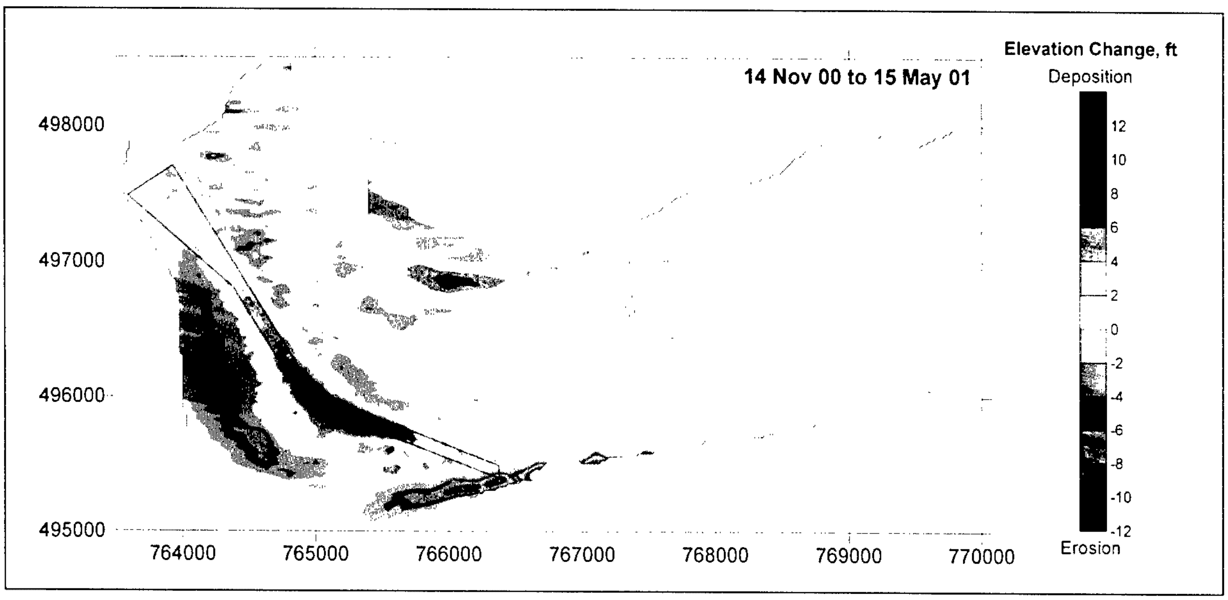


Figure 3-32. Bay Center Entrance Channel cumulative bottom change, 14 November 2000 to 15 May 2001

Cross sections were established at two locations (Figure 3-33). Cross-section profiles at Sections A and B are compared in Figures 3-34 and 3-35, respectively. Cross-sectional area differences were computed as erosion and deposition separately, in depth increments and by survey date. The computed area change is listed in Table 3-2 for Section A and Table 3-3 for Section B.

Hydrodynamic data collection in 2000-2001

Three instrument frames were fabricated, and each was equipped with an ADP and a sediment trap. The instrument frames were deployed near the eastern and western ends of Bay Center Entrance Channel (east and west stations, respectively) and midway along the channel (middle station), as shown in Figure 3-36. The frame deployed at the middle station also contained a SonTek Acoustic Doppler Velocimeter Ocean (ADVO) and two optical back-scatterance turbidity sensors (OBS-3). Figure 3-37 shows the frame and instruments that were deployed at the middle station.

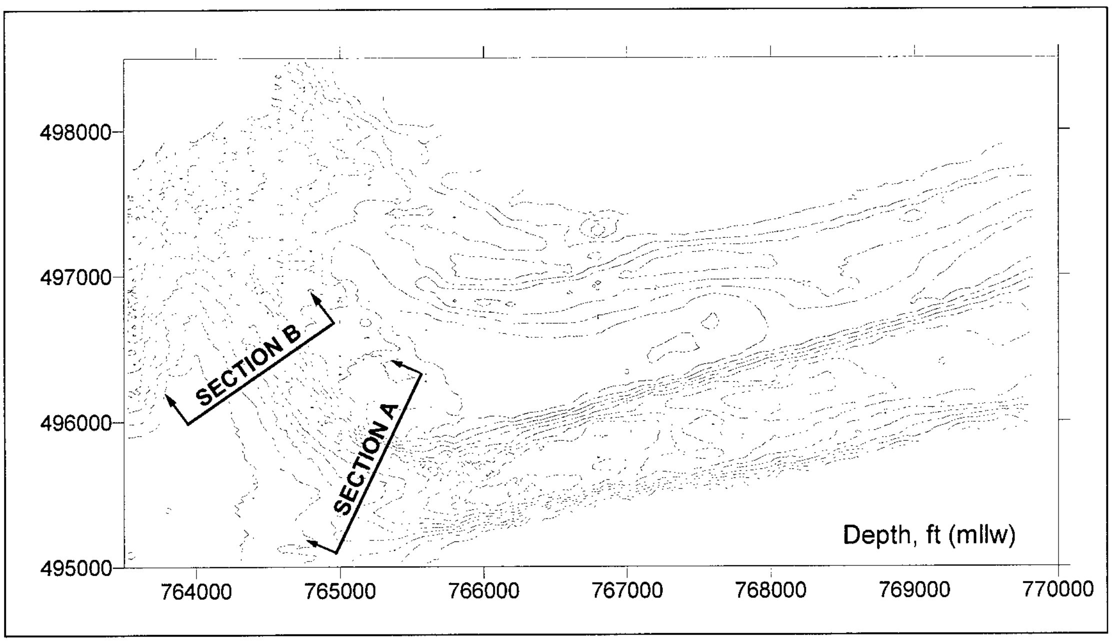


Figure 3-33. Location of Bay Center Entrance Channel cross sections A and B

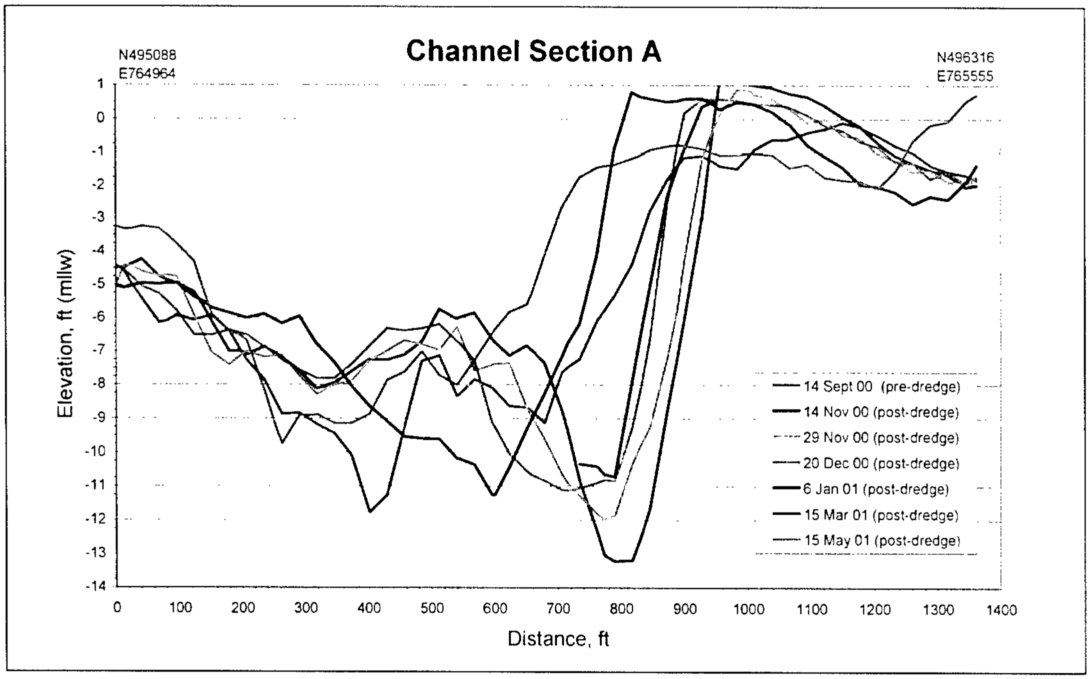


Figure 3-34. Postdredging cross-section profiles, Section A

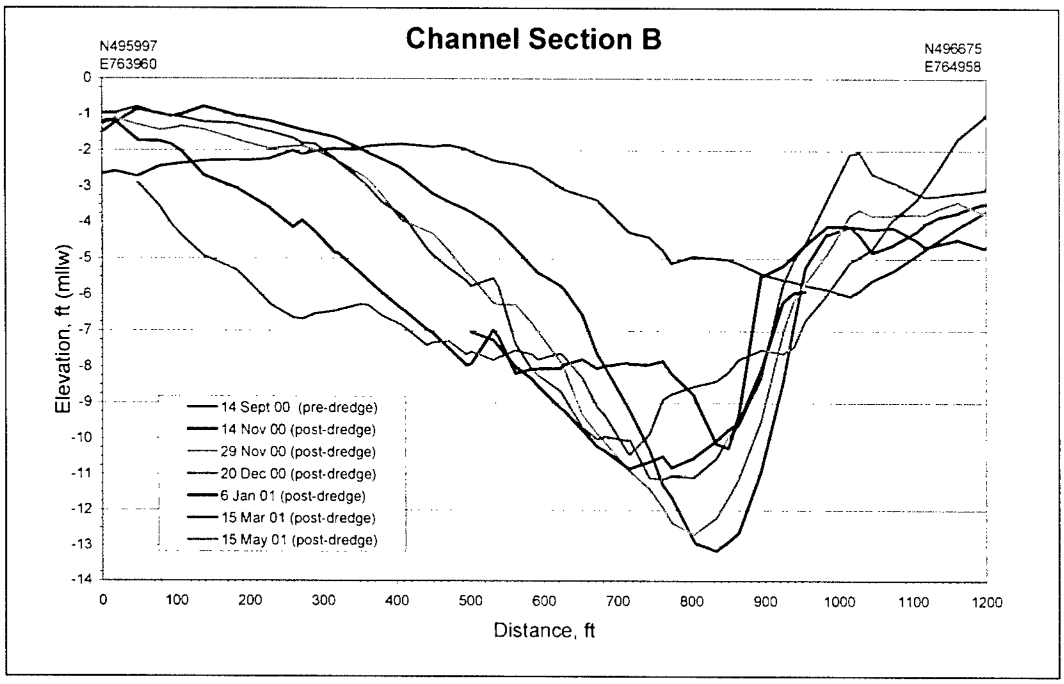


Figure 3-35. Postdredging cross-section profiles, Section B

Table 3-2
Erosion and Deposition by Depth Range and Survey Date, Section A

Section A
9/14/00 – 11/14/00*

Elevation (ft)	Erosion (ft^2)	Deposition (ft^2)	Net Change (ft^2)
(-15) – (-12)	74.3	0.0	-74.3
(-12) – (-8)	543.3	468.0	-75.3
(-8) – (-4)	552.2	548.8	-3.4
(-4) – 0	252.6	161.0	-91.6
>0	0.0	156.4	156.4
Total	1422.4	1334.2	-88.2

*Note: Calculations include channel dredging

Section A
11/14/00 – 11/29/00

Elevation (ft)	Erosion (ft^2)	Deposition (ft^2)	Net Change (ft^2)
(-15) – (-12)	0.0	74.3	74.3
(-12) – (-8)	131.7	144.1	12.4
(-8) – (-4)	254.2	84.6	-169.6
(-4) – 0	52.6	47.9	-4.7
>0	86.2	0.0	-86.2
Total	524.7	350.9	-173.8

Section A
11/29/00 – 12/20/00

Elevation (ft)	Erosion (ft^2)	Deposition (ft^2)	Net Change (ft^2)
(-15) – (-12)	0.0	0.0	0.0
(-12) – (-8)	182.8	133.2	-49.6
(-8) – (-4)	108.6	310.8	202.2
(-4) – 0	2.8	193.1	190.3
>0	19.1	34.8	15.7
Total	313.3	671.9	358.6

Section A
12/20/00 – 1/6/01*

Elevation (ft)	Erosion (ft^2)	Deposition (ft^2)	Net Change (ft^2)
(-15) – (-12)	0.0	0.0	0.0
(-12) – (-8)	0.0	55.3	55.3
(-8) – (-4)	0.0	51.6	51.6
(-4) – 0	22.2	8.1	-14.1
>0	12.3	0.0	12.3
Total	34.5	115.0	80.5

Section A
1/6/01 – 3/15/01

Elevation (ft)	Erosion (ft^2)	Deposition (ft^2)	Net Change (ft^2)
(-15) – (-12)	0.0	0.0	0.0
(-12) – (-8)	0.0	183.2	183.2
(-8) – (-4)	0.0	386.6	386.6
(-4) – 0	0.0	413.9	413.9
>0	0.3	73.0	72.7
Total	0.3	1056.7	1056.4

Section A
3/15/01 – 5/15/01

Elevation (ft)	Erosion (ft^2)	Deposition (ft^2)	Net Change (ft^2)
(-15) – (-12)	0.0	0.0	0.0
(-12) – (-8)	173.1	496.6	323.5
(-8) – (-4)	259	645.1	386.1
(-4) – 0	345.8	488.0	142.2
>0	122.5	18.4	-104.1
Total	900.4	1648.1	747.7

Table 3-3
Erosion and Deposition by Depth Range and Survey Date, Section B

Section B
9/14/00 – 11/14/00*

Elevation (ft)	Erosion (ft^2)	Deposition (ft^2)	Net Change (ft^2)
(-15) – (-12)	70.7	0.0	-70.7
(-12) – (-8)	681.9	0.0	-681.9
(-8) – (-4)	1051.5	197.9	-853.6
(-4) – 0	377.6	400.5	22.9
>0	0.0	0.0	0.0
Total	2181.7	598.4	-1583.3

*Note: Calculations include channel dredging

Section B
11/14/00 – 11/29/00

Elevation (ft)	Erosion (ft^2)	Deposition (ft^2)	Net Change (ft^2)
(-15) – (-12)	8.7	48.2	39.5
(-12) – (-8)	195.0	88.5	-106.5
(-8) – (-4)	365.9	73.0	-292.9
(-4) – 0	320.1	41.2	-278.9
>0	0.0	0.0	0.0
Total	889.7	250.9	-638.8

Section B
11/29/00 – 12/20/00

Elevation (ft)	Erosion (ft^2)	Deposition (ft^2)	Net Change (ft^2)
(-15) – (-12)	0.0	31.2	31.2
(-12) – (-8)	38.3	222.6	184.3
(-8) – (-4)	94.6	117.4	22.8
(-4) – 0	9.4	287.5	278.1
>0	0.0	0.0	0.0
Total	142.3	658.7	516.4

Section B
12/20/00 – 1/6/01*

Elevation (ft)	Erosion (ft^2)	Deposition (ft^2)	Net Change (ft^2)
(-15) – (-12)	0.0	0.0	0.0
(-12) – (-8)	57.7	56.0	-1.7
(-8) – (-4)	123.7	0.8	-122.9
(-4) – 0	0.0	0.0	0.0
>0	0.0	0.0	0.0
Total	181.4	56.8	-124.6

Section B
1/6/01 – 3/15/01

Elevation (ft)	Erosion (ft^2)	Deposition (ft^2)	Net Change (ft^2)
(-15) – (-12)	0.0	0.0	0.0
(-12) – (-8)	8.8	477.3	468.5
(-8) – (-4)	12.1	125.7	113.6
(-4) – 0	0.0	0.0	0.0
>0	0.0	0.0	0.0
Total	20.9	603	582.1

Section B
3/15/01 – 5/15/01

Elevation (ft)	Erosion (ft^2)	Deposition (ft^2)	Net Change (ft^2)
(-15) – (-12)	0.0	0.0	0.0
(-12) – (-8)	189.6	100.4	-89.2
(-8) – (-4)	761.9	101.4	-660.5
(-4) – 0	239.2	196.0	-43.2
>0	0.0	0.0	0.0
Total	1190.7	397.8	-792.9

Figure 3-36. Locations of instrument frames at Bay Center Entrance Channel

Instrument frames were deployed at the three stations from 16 June to 26 July 2000 to document predredging hydrodynamics near Bay Center Entrance Channel. Instrument packages for this first deployment consisted of an ADP configured to operate at 1,500 kHz for recording nondirectional wave data, water level, and current through the water column in 0.5-m bins. The OBS-3 sensors deployed at the middle station were calibrated to measure suspended sediment concentration (SSC). Twenty-nine water samples were collected at nine stations on 16 June 2000 at near-bottom, middepth, and near-surface positions. The samples were then analyzed for Total Suspended Solids (TSS) to document sediment concentration in the water column. Figure 3-38 shows the location of the TSS sampling sites.

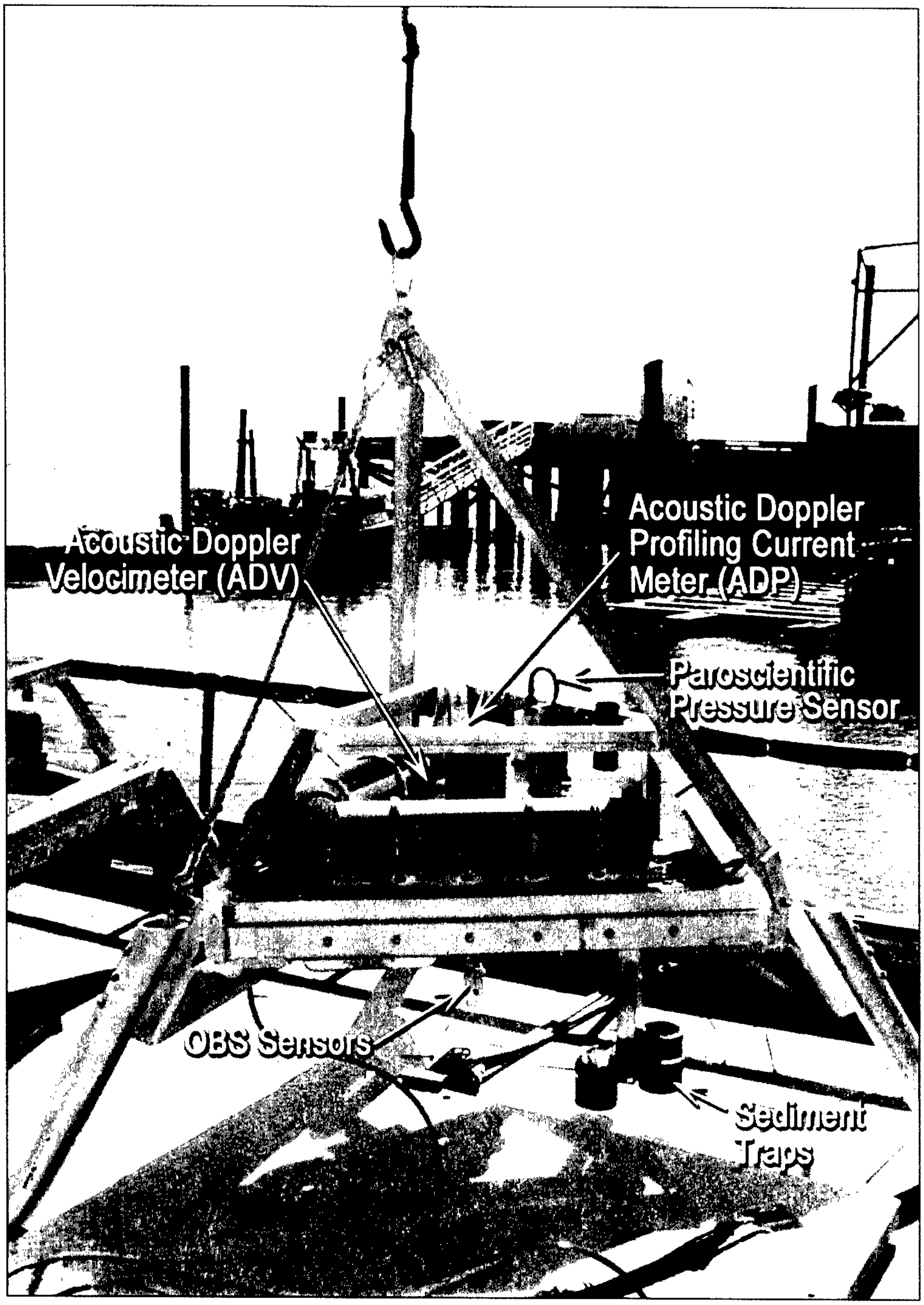


Figure 3-37. Instrumentation and mounting frame deployed at middle station

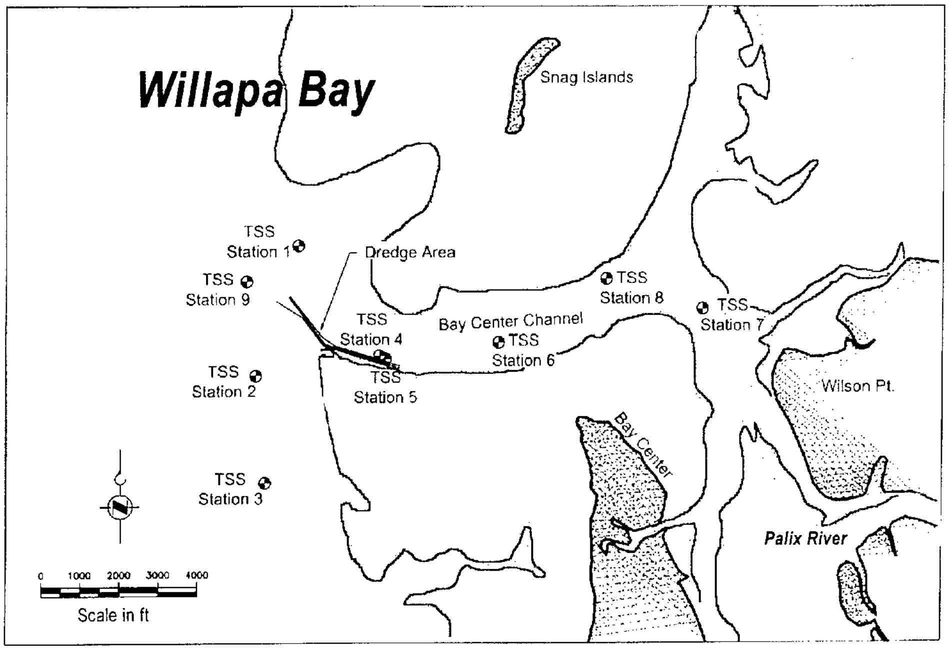


Figure 3-38. Location of TSS sampling

The second deployment followed completion of dredging and took place on 7 November 2000. Instrumentation consisted of an ADP at all three stations for recording nondirectional wave data, water depth by means of a pressure sensor, and vertical profile of current. The middle station also contained the hydra system for the postdredging deployments. On 8 December 2000, the instruments were serviced, data were downloaded, and the instrumented frames were redeployed. On 7 February 2001, all the equipment was recovered, and the sites were demobilized.

Data processing methods

Time series measurements of waves, currents, suspended sediment concentration, and bed level collected during three instrument deployments were analyzed to understand the sources and mechanisms that shoal the channel and to aid in verifying numerical calculations of sediment transport and bottom change. Processed data for the three deployment periods are displayed in the Bay Center Entrance Channel data report (PI Engineering 2001b). Time series of water depth h, horizontal components of along-channel (x-component) and across-channel (y-component) of near-bottom velocity V_x and V_y, suspended sediment concentration (SSC), and bed elevation relative to the instrument frame were obtained after processing sensor data collected by the SonTek Hydra system, located on the frame at the middle station. Time-varying profiles of current speed $|V_{(z)}|$ and direction $\theta v_{(z)}$, where z is the elevation above the bed, were obtained and analyzed from the ADP systems located on the east, middle, and west stations.

Pressure measurements were converted to static water column height above the sensor by applying formulas incorporating calculated water density and mean barometric pressure recorded at the Hoquiam, Washington airport. Measured water temperature and estimated salinity were converted to water density by using the International Equation of State of Seawater 1980 (IES80) (UNESCO 1983). The measured height of the pressure sensor above the bed was added to yield (hydrostatic) water depth.

Static water depths were converted to water-surface elevation η series suitable for wave height and period calculation by correcting for pressure attenuation as a function of h and wave frequency f. Corrections were carried out in the frequency domain and converted to the time domain for output and calculation of wave statistics. The attenuation correction is based on the linear wave theory dispersion relationship. A maximum cutoff frequency (Earle and McGehee 1995) dependent on h was also applied to the processed data. Significant wave height H_s was determined as $H_{1/3}$, the average of the highest third of the waves, from a zero up-crossing analysis of η.

High-resolution measurements of near-bottom (nominal elevation of 35 cm from the bottom) horizontal velocity acquired as magnetic north and east constituents V_n and V_e were corrected to true north by applying the local magnetic declination (18.6 deg east of north) and then aligned with the principal axis of motion. The primary axis (x) was determined by computing the velocity variance in 1-deg increments from zero to 360 deg and applying the angle of maximum variance to rotate the horizontal velocity components. The alignment of V_x corresponds closely with the channel axis and V_x is hereafter referred to as the along-channel current. The secondary component, V_y, is at right angles to V_x and is therefore referred to as cross-channel current.

Vertical profiles of $|V_{(z)}|$ and $\theta v_{(z)}$, were collected at each station with an ADP during a 3-min sample period beginning every 6 min. Each recorded vertical profile consists of velocity measurements in a fixed number of cells above the instrument, spaced at 0.5-m intervals. The first cell begins 0.9 m above the instrument and the most distant (top) cell is programmed during instrument setup to be above the water surface at high tide with high wave conditions. The data in cells above the water surface at the time of the measurement are removed during processing.

ADP data were extracted from the raw data files and corrected for magnetic declination. ADP pressure measurements were converted to water column height above the ADP using mean barometric pressure and water density (calculated from temperature and estimated salinity) during the deployment period. The mean water depth during the recording of each current profile served as a reference height to eliminate values from those cells that were above the water surface and one cell (0.5 m) below the water surface. Eliminating one cell below the water surface removed wave effects from the velocity record. Horizontal north and east velocity components, referenced to magnetic north, were corrected to true north by applying the local magnetic declination (18.6 deg east of north).

OBS counts were converted to SSC predeployment calibration coefficients. The OBS were calibrated in a turbidity tank with bed sediment taken from the project site prior to the deployment. The deployment depth of the OBS sensors and the relatively small waves present at the site precluded measurement of

wave-induced sediment suspension. Because the dominant suspension and transport is assumed to be from tidal currents, only burst-averaged SSC data (4,096 samples at 4 Hz) were analyzed. Time series were inspected for evidence of biofouling and sensor burial. Biofouling and the approach to burial are indicated in the SSC signal by rising background or a change in the sensor offset. Complete burial is indicated by a significant change in sensor offset. Subjective estimates were made of the degree of biofouling or burial, and data were discarded accordingly.

The distance from the bed to the ADVO transducer is recorded at the beginning of each sampling burst. The ADVO acoustically measures the distance to the solid boundary and records a distance when three estimates of boundary position agree within 1 mm. The measured distance is converted to elevation relative to the base of the tripod legs. Negative relative elevations indicate scour below the tripod legs while positive elevations indicate net deposition. Although each distance measurement is accurate, changes in the frame orientation (instrument pitch and roll) and sinking of the tripod into the sediment as a result of scour can lead to uncertainties in determining bed elevation change.

Time domain cross-correlation analysis and ensemble-averaging of time series data as a function of tidal current phase were performed to reveal temporal relationships within average tidal cycles between waves, currents, water depths, suspended sediments, and bed levels. Ensemble-averaging, as opposed to time-averaging, was adopted to retain the temporal variation in measured parameters over a tidal cycle. Depth-averaged velocities from the ADP were aligned with the principal axis of motion as previously described. A zero-up-crossing analysis was applied to the depth-averaged V_x and used as a basis for separating individual tidal cycles. The flood phase of velocity occurs between 0 and π radians, whereas the ebb phase occurs between 1 and 2π radians. Each cycle was then divided into an equal number of phase intervals corresponding to the ebb and flood of the tidal velocity cycle. Corresponding observations of h, $|V_{(z)}|$, $\theta v_{(z)}$, SSC, H_s, and relative bed elevation, occurring within similar phase intervals, were then ensemble-averaged to represent variation over an average tidal cycle.

Multiplying the time-varying SSC by horizontal current speed yields the horizontal suspended sediment flux at a point. Summing the instantaneous fluxes thus obtained over time provides an indication of the relative contributions to the gross suspended sediment flux.

First deployment – prior to dredging

The first deployment (16 June to 26 July 2000) was characterized by large net deposition of fine sand (median grain size D_{50} of 125 μm) at the east, middle, and west stations. This general statement is supported by the following observations:

a. Oxidation marks on the legs of all instrument frames indicate that 40 to 60 cm of accretion were present at the time of recovery.

b. Low-signal amplitude data from the ADPs on the middle and west stations indicate that the top of the instruments, (1 m above the bottom

when deployed) were covered by sand for 10 and 16 days, respectively. The middle station was covered by sand at the time it was recovered.

c. The instrument frame at the middle station was covered with substantial amounts of sand at periods during the first deployment. Figure 3-39 shows time series plots of synchronous water depth, easting and northing velocity components (*Ve*, *Vn*), relative bottom elevation, and output for two OBS-3 sensors located at heights of 0.15 m and 0.25 m above the base of the middle station frame.

d. The ADVO boundary measurements indicate that approximately 10 cm of erosion occurred under the instrument frame during the first 2 to 3 days of spring tidal flows following deployment (16 June through 19 June). The erosion was followed by at least 30 cm of accretion over the next 2 days (19 June through 21 June), apparently coinciding with declining ebb-flood current speeds following the peak spring tide range. The bottom OBS-3 sensor at 0.15 m elevation above the base of the frame was buried approximately 5 days after deployment. The top OBS-3 sensor and ADVO sampling volume at 0.25 m above the base of the frame were buried 2 days later and provided no further velocity or boundary data. The ADVO data reveal that the sensor might have been uncovered briefly for 2 days during the large spring tides in the first week of July. During this period, the platform tilted substantially and the ADVO sensor was then buried again.

e. The combined ADVO/OBS/ADP data indicate a cumulative sand deposition of 20 to 25 cm/week, with a daily deposition or erosion of about 10 cm during spring tides.

Because of the short period of useful data and the large fluctuations in bed elevation relative to the sensors during that period, the near-bottom measurements of currents and suspended sediments from the first deployment have not been analyzed further.

Sediment traps were attached to the middle station instrument frame during predredging and postdredging deployments and the samples were analyzed for size characteristics. Size analyses of four sediment samples were reported as percent retained in phi-unit size classes between 4.75 mm and 0.001 mm. One predredging sample was collected from the portion of the frame that had become partially buried during the deployment. A second sample was collected at a height of 25 cm above the bottom. One postdredging sample was collected 35 cm above the bottom, and a second collected 105 cm above bottom. The percent by weight retained on the 0.125-mm sieve (3-phi class) ranged between 75 and 85 percent for all samples. Only subtle differences distinguished one sample as being finer or coarser than another. The sum of the 3- and 4-phi classes in each sample ranged between 80 and 87 percent. The differences correspond with elevations above channel bottom only for the postdredging samples. The lower-elevation sample contained a slightly higher percent of fines than did the higher-elevation sample for the predredging deployment.

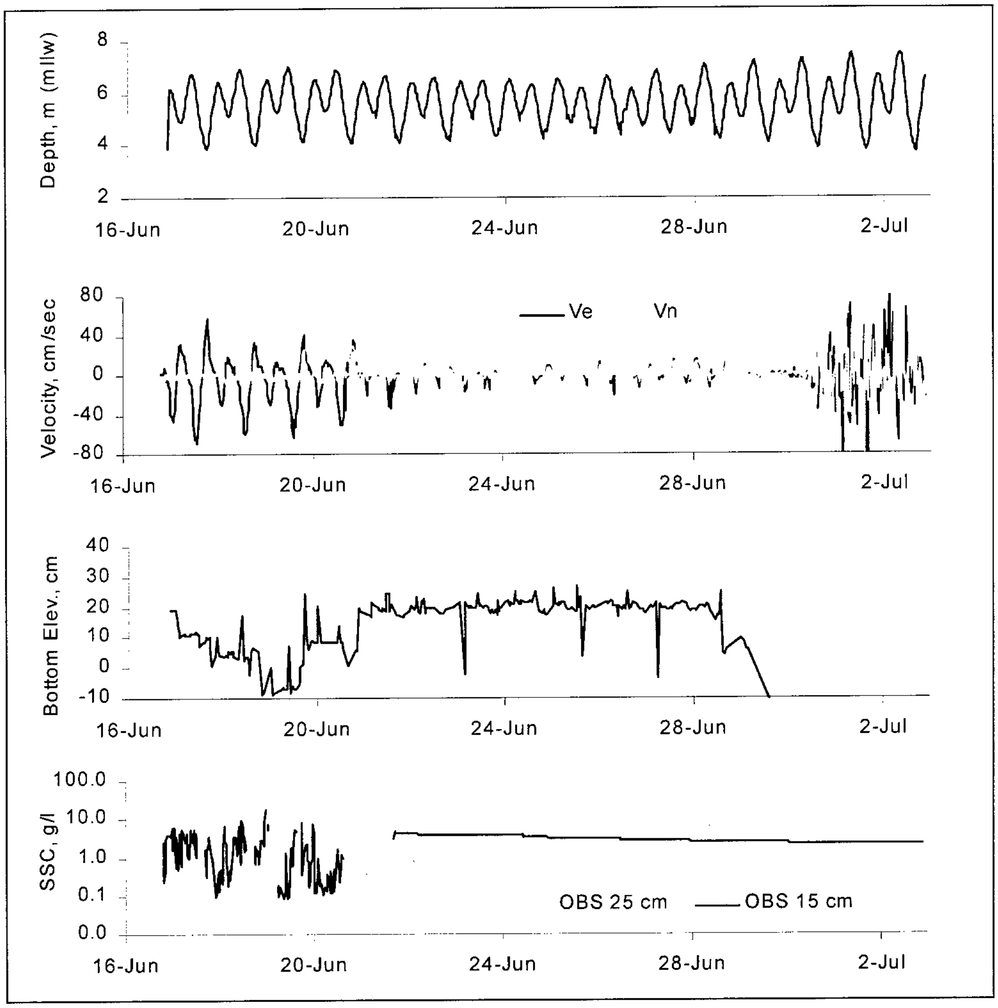


Figure 3-39. Time series plots of water depth, near-bed velocity components (V_e, V_n), bottom elevation relative to ADVO, and SSC during first 2 weeks of deployment 1 at middle station

Second and third deployments – postdredging

Figure 3-40 shows representative time series of h, V_x and V_y, H_s, and SSC from the middle station during the second deployment.

Significant wave height H_s varies between 0 m and just over 0.4 m during the deployment, and H_s increases and decreases in phase with h. Application of a wave growth model in a large estuary in New Zealand (Black et al. 1999) showed that a similar variation in H_s is driven by the increase in fetch associated with harborwide submergence and emergence of sand banks that accompany the rise and fall of the tide. Similarly, throughout the rise and fall of the tide in Willapa Bay, the geometry of the estuary and the wind strength and direction control the magnitude and variation of wave height.

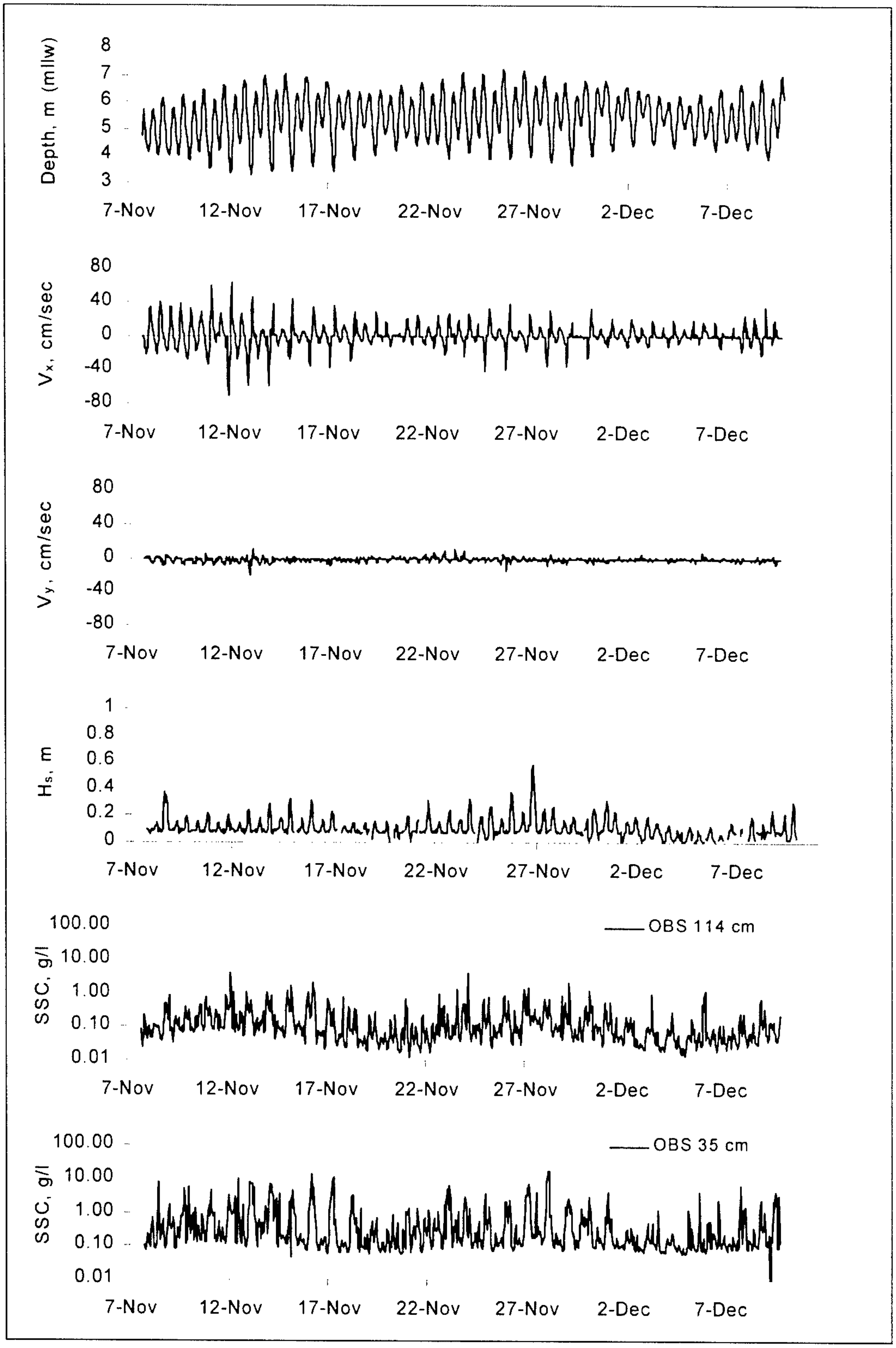


Figure 3-40. Time series of depth h, velocity (V_x, V_y), significant wave height H_s, and SSC at middle station during deployment 2

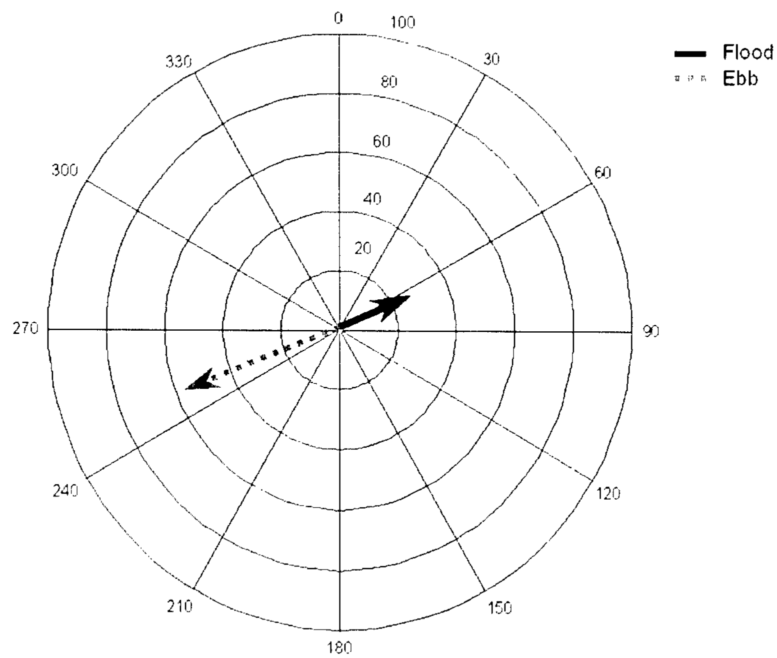
Furthermore, observations by Green, Black, and Amos (1997) suggest that even a modest increase in H_s over the tidal flats at high tide results in a band of significantly elevated SSC in the region where wave orbital motion and turbulence due to wave breaking can entrain bottom sediments. The turbid fringe can then be advected into channels adjacent to the tidal flats during the following ebb. Analysis of suspended sediment concentration data lead to the conclusion that a similar process may be occurring at Bay Center. The analysis is described in the following section.

Sediment flux

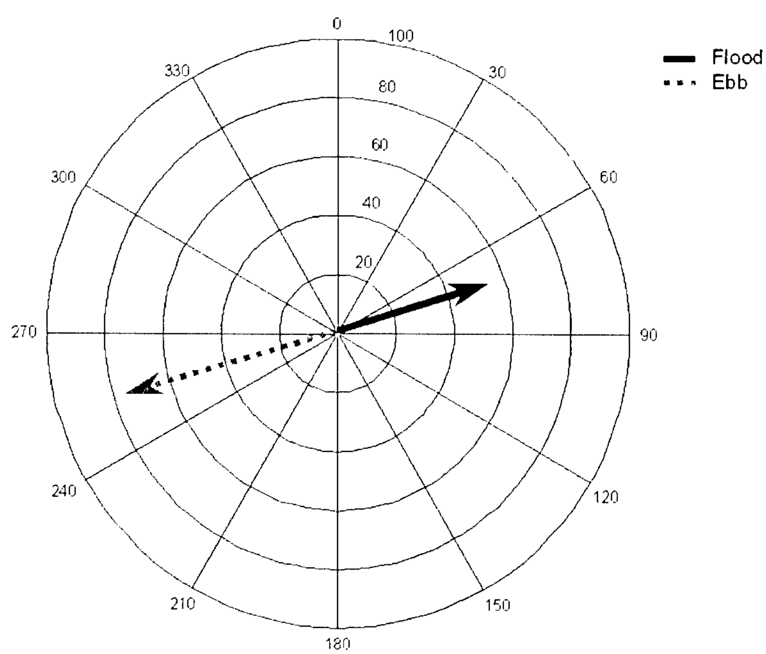
The ADV near-bottom components V_x and V_y correspond approximately with along- and across-channel flows, respectively, as confirmed by the orientation of the depth-averaged peak ebb and peak flood current vector plots shown in Figure 3-41. The vector orientations show that the dominant flows are aligned with the channel axis at each location. Vector magnitudes indicate that the Bay Center Entrance Channel is ebb-dominated, whereas the west side of the Nahcotta Channel near the mouth of the Bay Center Entrance Channel is flood-dominated. The across-channel component of velocity is minor in comparison with the along-channel component.

Peaks in burst-averaged SSC up to 10 g/l occur in each tide cycle, the primary peak mostly associated with the ebb slack (Figure 3-41). The tidal daily maximum of SSC also varies over a longer time scale, increasing during spring tides and decreasing during neaps. SSC is generally higher at the lower elevation (0.35 m) than at the upper measurement elevation (1.14 m). The spring neap-variation is more pronounced at the upper elevation than at the lower elevation.

Time series of water depth h and bed level measured by the ADVO during deployments 2 and 3 are shown in Figure 3-42. At the beginning of the deployment the bed exhibited a number of short-duration erosion-deposition cycles. The deposition associated with these approximately diurnal cycles coincides mainly with low-water slack, in phase with the largest near-bed SSC. Also evident is a longer-term variation in bed elevation associated with the spring-neap cycle. There is a tendency for bed erosion as tide range increases from neap to spring range and for deposition during spring to neap transitions or during moderate springs. During the latter part of the third deployment the diurnal variability in the bed elevation appeared to be less, possibly indicating some stabilization of the channel following a more dynamic postdredging period of readjustment.

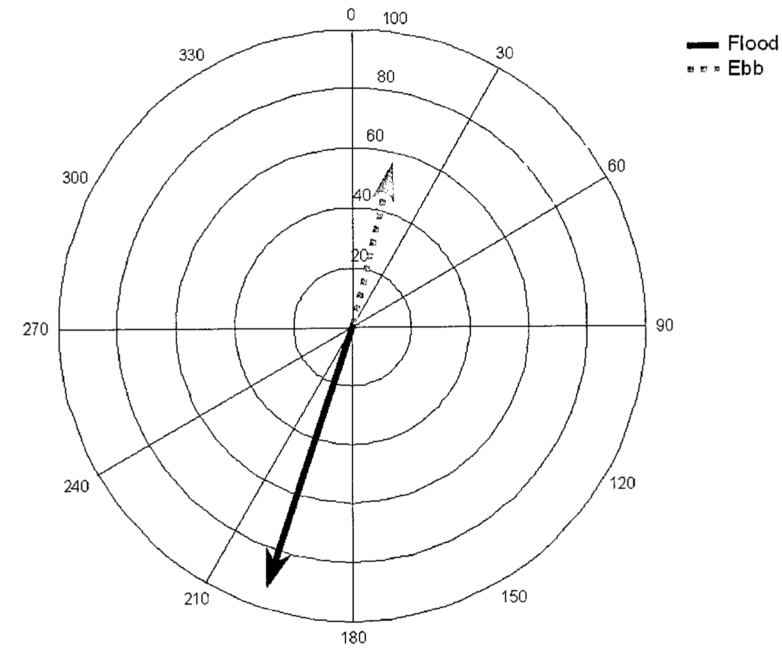


a. East station deployment 2: Depth-averaged peak ebb and flood current



b. Middle station deployment 2: Depth-averaged peak ebb and flood current

Figure 3-41. Compass plots showing depth-averaged and burst-averaged peak ebb and peak flood current vectors during deployment 2 at east (a), middle (b), and west (c) stations (continued)



c. West station deployment 2: Depth-averaged peak ebb and flood current

Figure 3-41. (Concluded)

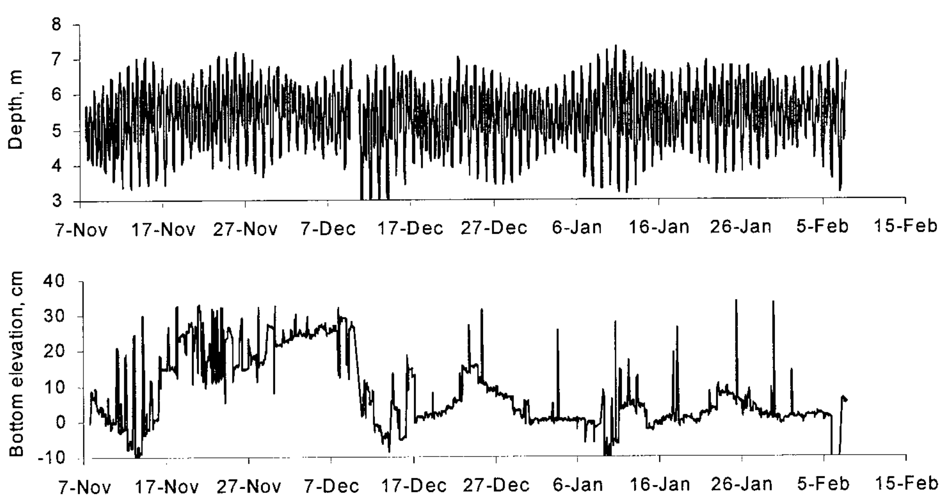


Figure 3-42. Time series of water depth *h* and bottom elevation relative to ADVO probe at middle station during deployments 2 and 3 (Note: Platform was removed/replaced 9-10 December 2000)

Figure 3-43 shows ensemble-averaged and depth-averaged speed $|V_z|$, current direction $\theta v_{(z)}$, and corresponding ensemble-averaged h, H_s, SSC, and bed level as a function of tidal phase for the middle station. The maximum SSC at 1.14 m elevation occurs just after the maximum current speed on the flood and somewhat later on the ebb. Near the bed, the maximum SSC coincides with low water and ebb slack. Ensemble-averaged H_s exhibits a rapid increase during the latter stages of the flood, reaching a maximum at high tide, and followed by a less rapid decrease as the tide falls. Bed levels exhibit a maximum elevation just after the start of the flood, following the near-bed peak in SSC at ebb slack. A rapid decrease in bed level suggests most of the newly deposited sediment is again remobilized during the flood phase. There is a slight deposition again at high tide followed by pronounced erosion again on the ebb.

Ensemble-averaged and depth-averaged $|V_z|$, and $\theta v_{(z)}$ at the east and west stations are shown with corresponding ensemble-averaged h in Figures 3-44 and 3-45. Figures 3-46 to 3-48 illustrate ensemble-averaged profiles of $|V_z|$ and $\theta v_{(z)}$ together with the ensemble-averaged h for comparison. The profiles have been separated into ebb and flood phases. Maximum current speeds are reached at approximately mid-rising and mid-falling tides. At the middle and east stations (Figure 3-43 and 3-44) greater speeds are reached during the ebb and the velocity profiles (Figure 3-46 and 3-47) have a larger gradient, indicating greater bed shear stress. Current direction is more variable during flood phases than ebb phases at those locations. At the middle station, the current turns from approximately east to south at the end of the flood phase and then turn to approximately west during the ebb. At the west station, on the eastern edge of Nahcotta Channel, the current is flood-dominated. Current direction varies considerably, both through time and with elevation during the ebb phase at the west station. The current turns clockwise from south-southwest on the flood, to north-northeast, east, then back to north-northwest on the ebb.

Figure 3-49 shows times series of water-surface displacement $\Delta\eta$, depth-averaged velocity $|V|$ and direction θ_V from the west and middle stations for a portion of the second deployment. During the flood, the maximum $|V|$ at the west station lags behind the maximum $|V|$ at the middle station. Flood currents are divergent with the dominant current at the west station to the south-southwest and at the middle station to the east. During the ebb, currents are convergent. At the middle station, the westerly current continues to accelerate while the north-easterly current at the west station is already decelerating. Deceleration at the middle station coincides with ebb slack at the west station.

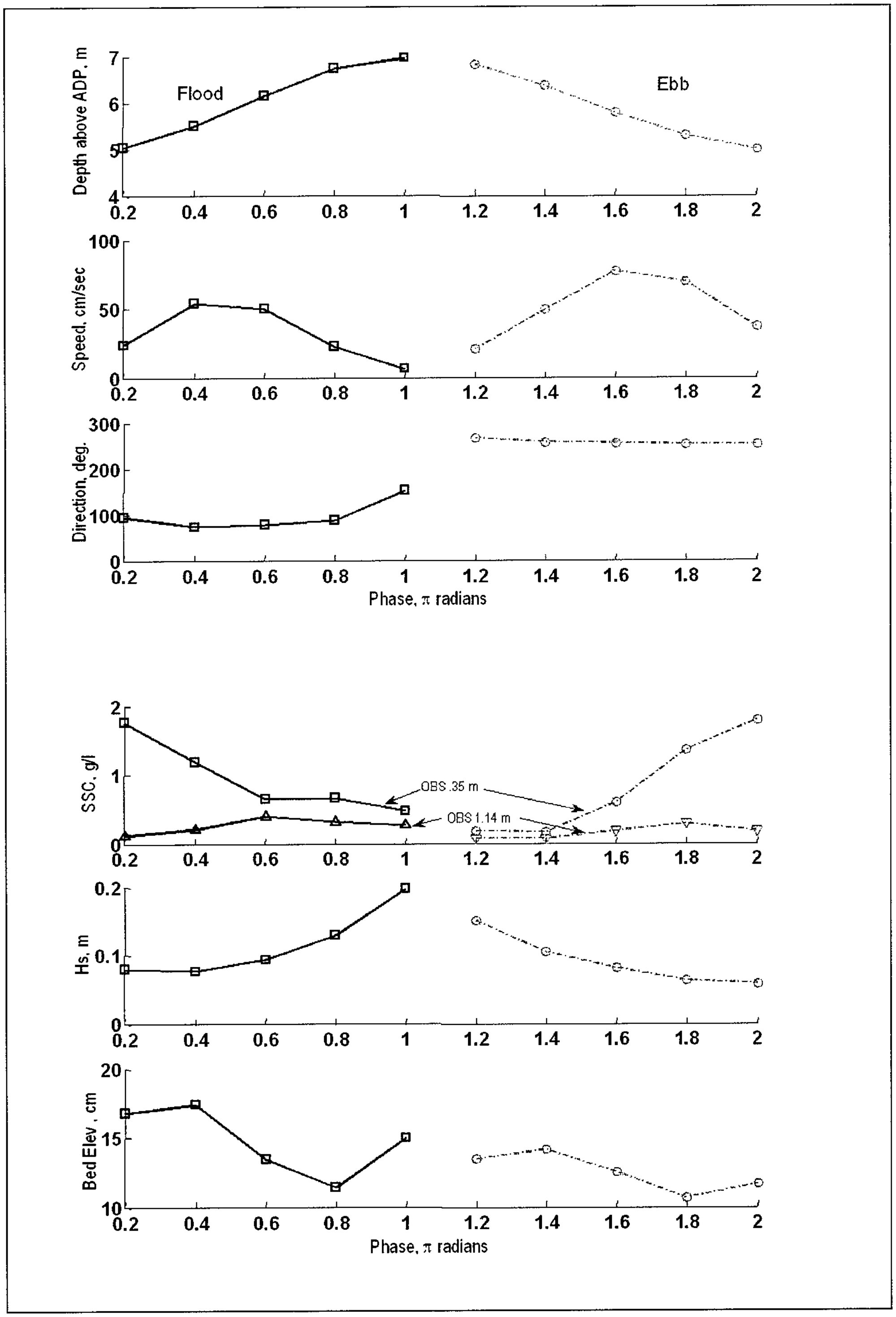


Figure 3-43. Ensemble-averaged water depth, depth-averaged current speed and direction, SSC, significant wave height H_s, and bed level as a function of tidal current phase for middle station during deployment 2

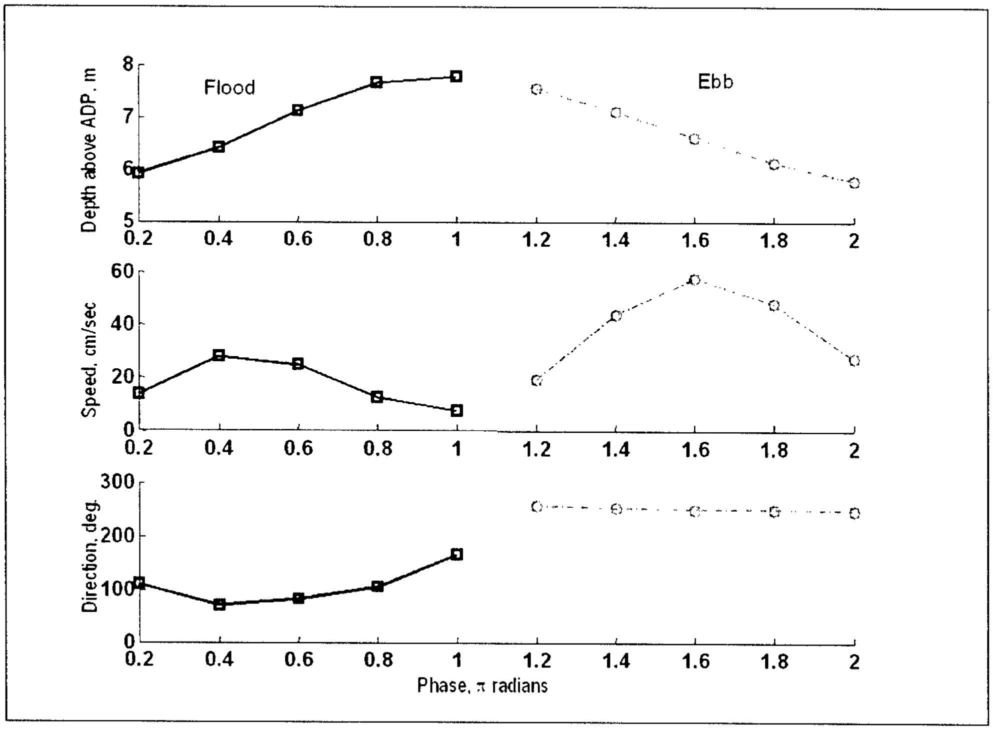


Figure 3-44. Ensemble-averaged water depth and depth-averaged current speed and direction at east station

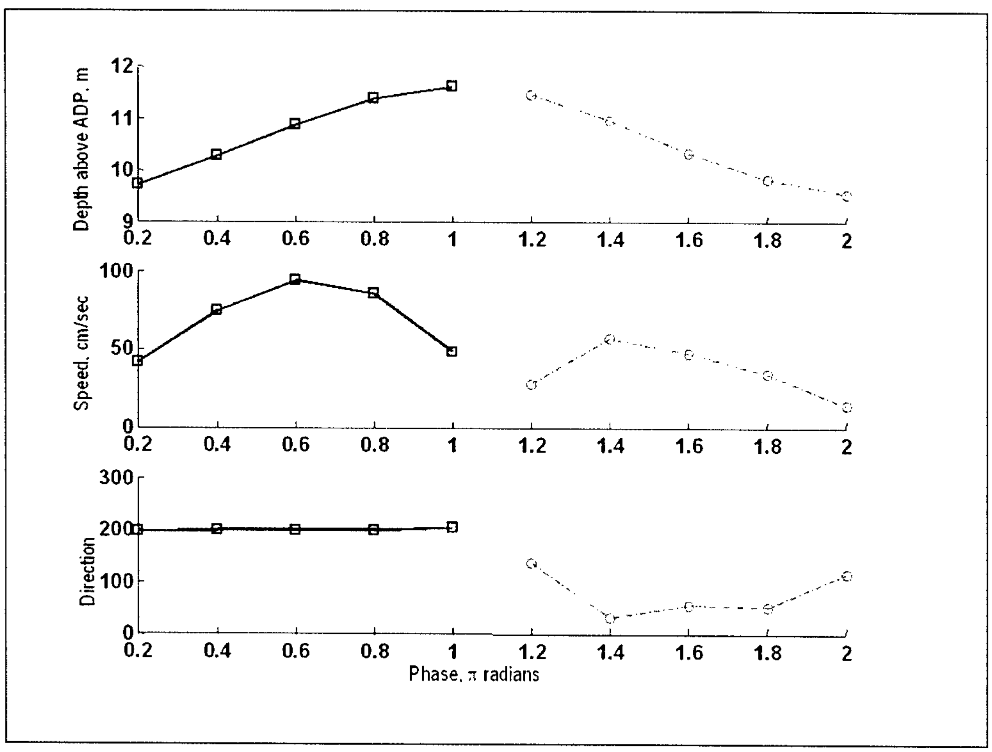


Figure 3-45. Ensemble-averaged water depth and depth-averaged current speed and direction at west station

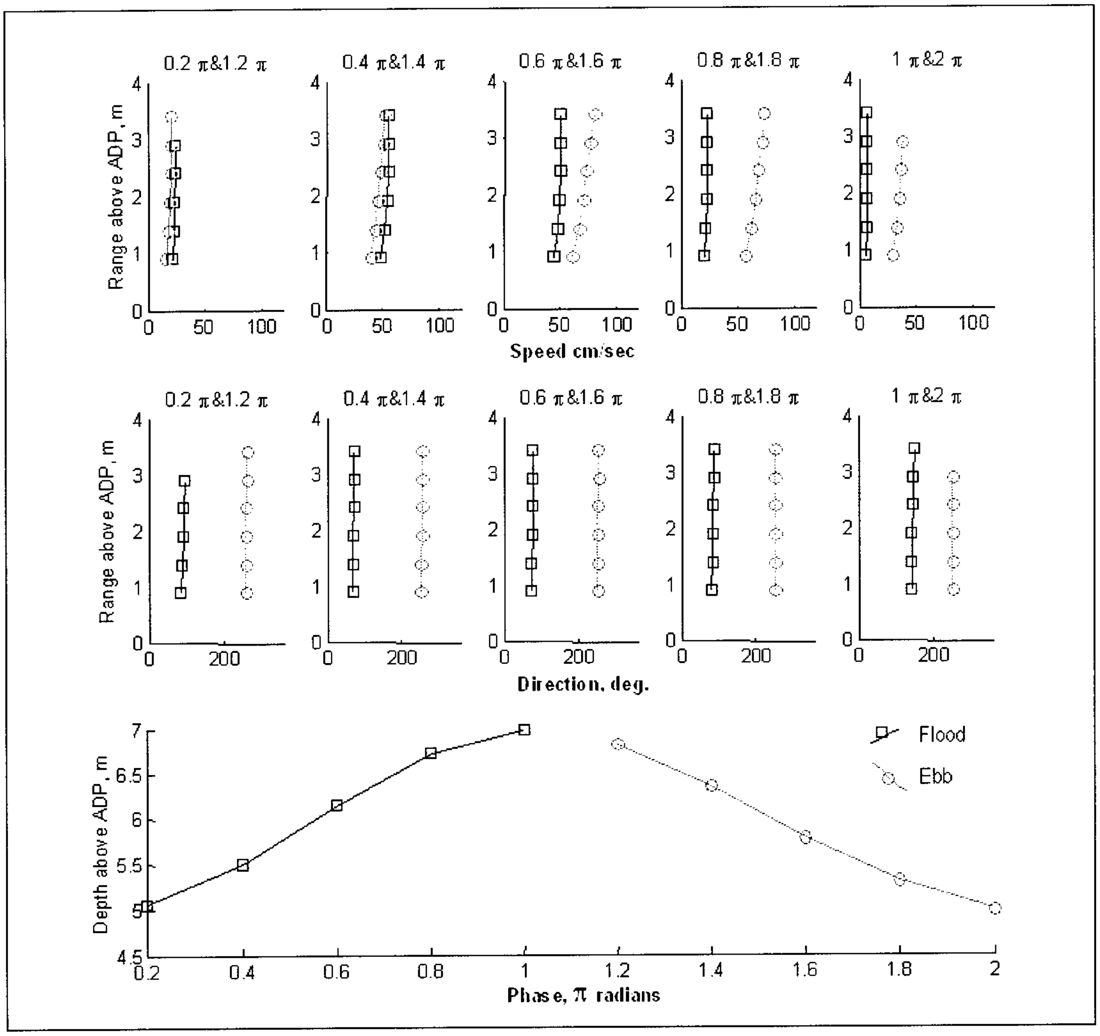


Figure 3-46. Ensemble-averaged profiles of speed and direction together with ensemble-averaged water depth for comparison at middle station

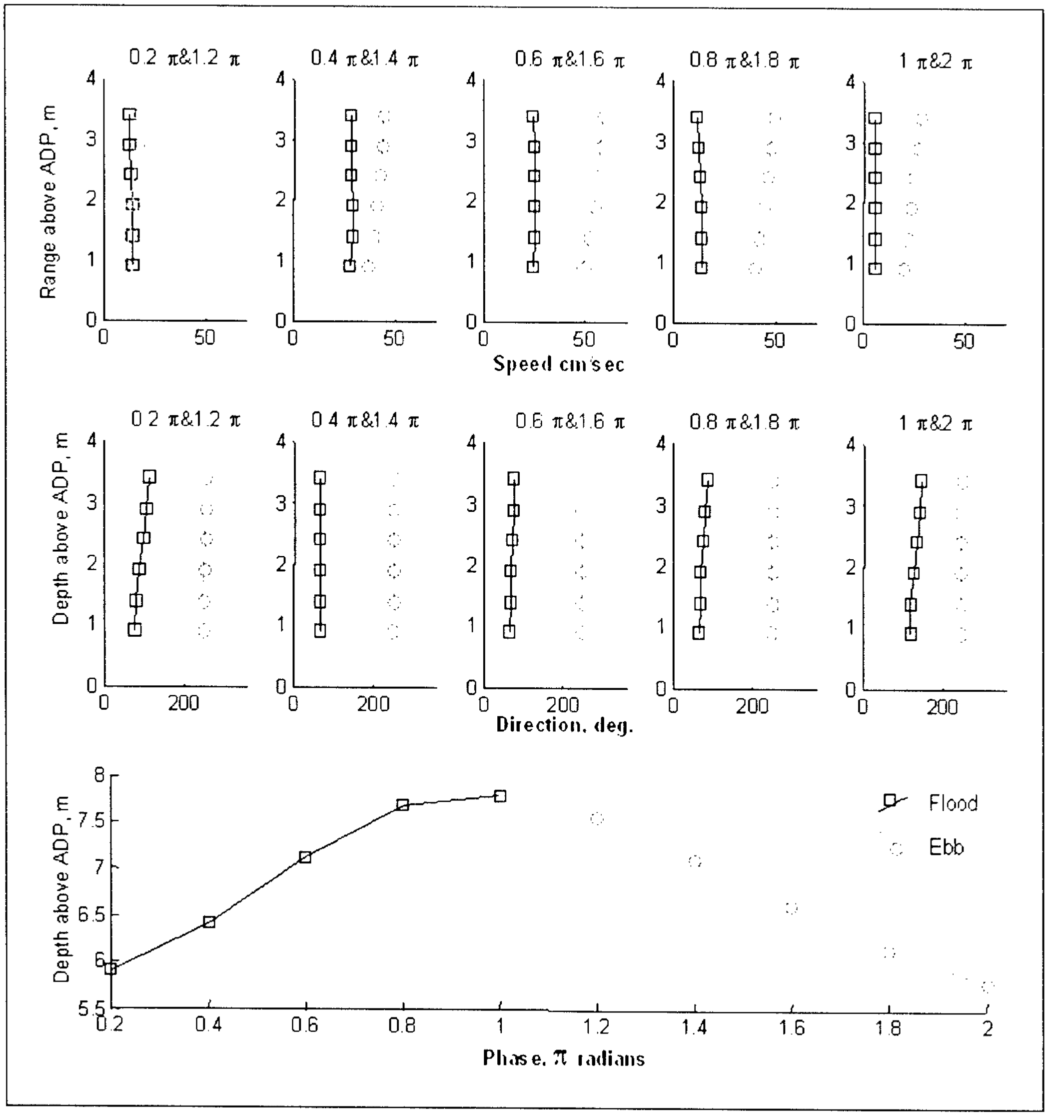


Figure 3-47. Ensemble-averaged profiles of speed and direction together with ensemble-averaged water depth for comparison at east station

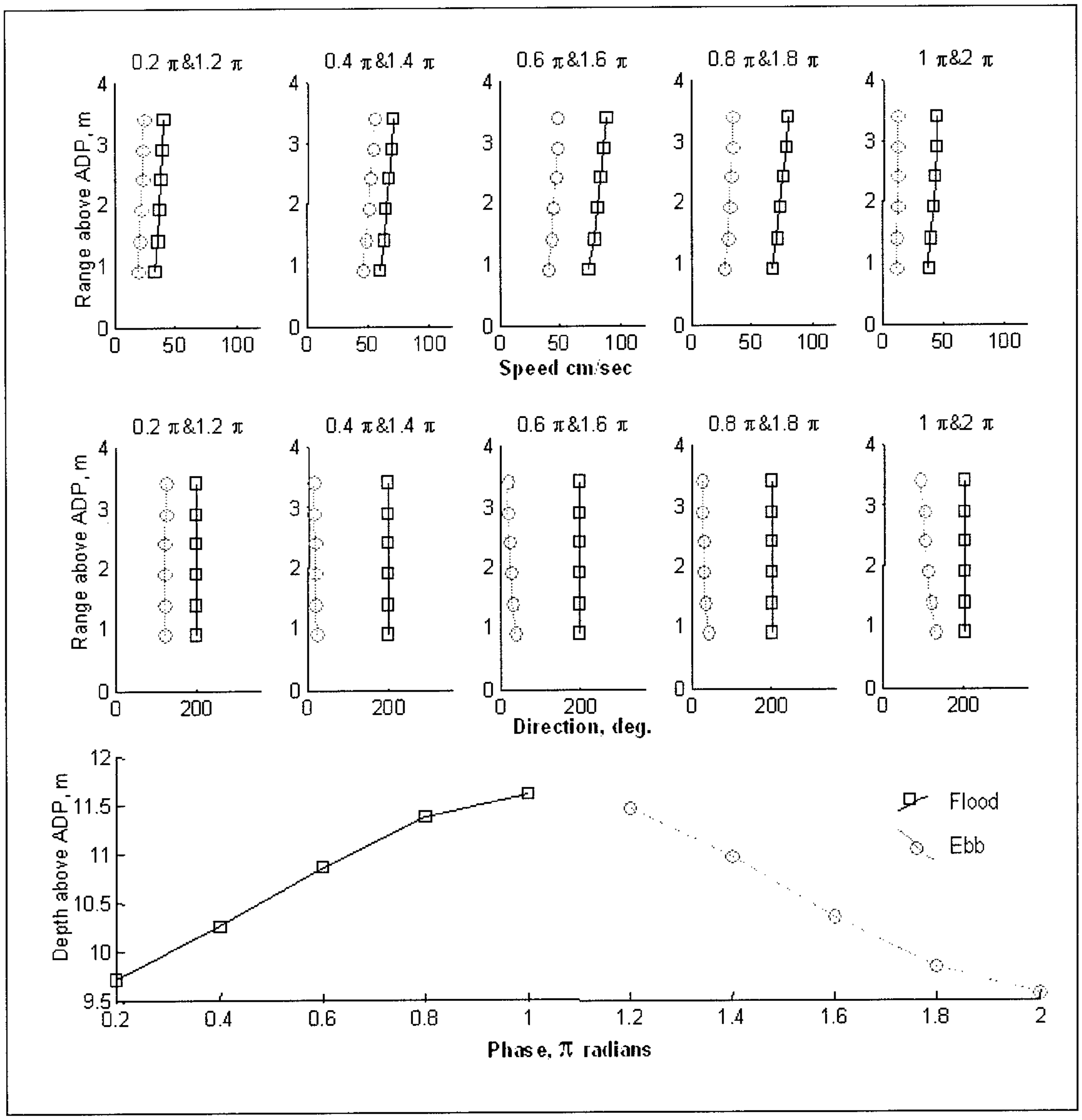


Figure 3-48. Ensemble-averaged profiles of speed and direction together with ensemble-averaged water depth for comparison at west station

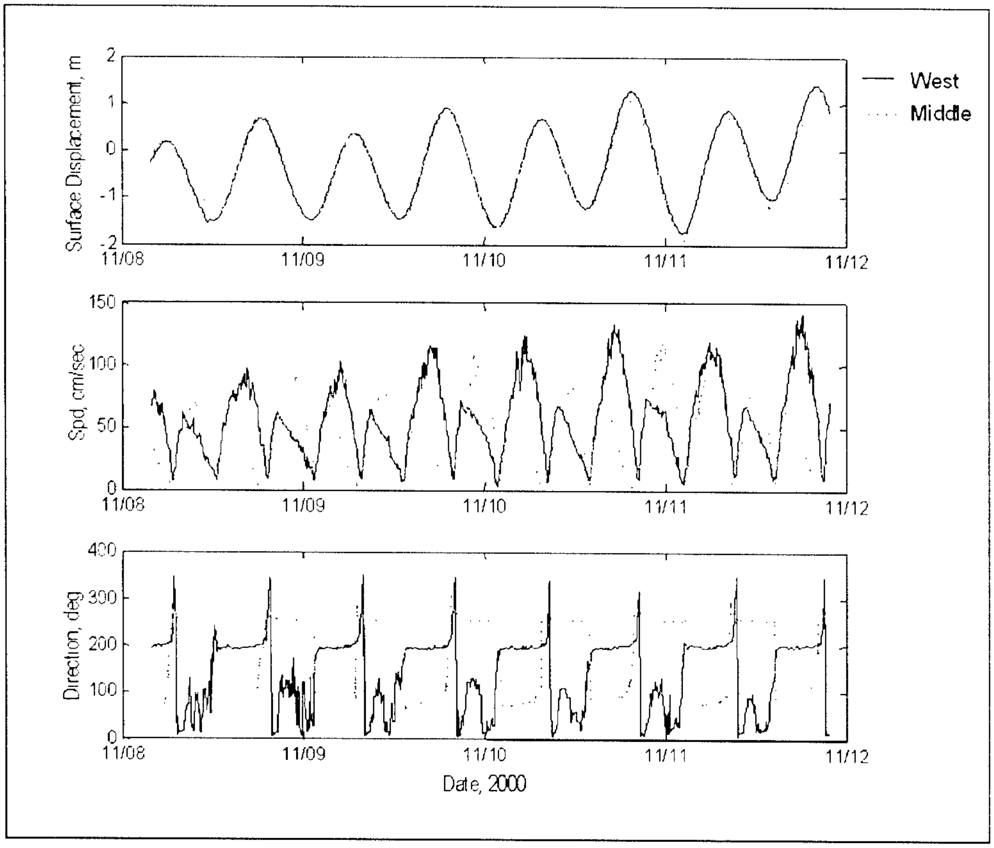


Figure 3-49. Times series of water-surface displacement ($\Delta\eta$), depth-averaged current speed and direction from west and middle stations for portion of deployment 2

Depth-averaged current speeds measured by ADP are summarized for the three stations and the three deployments in Table 3-4. The eastern side of the Nahcotta Channel is flood dominated with currents directed approximately south on the flood and north on the ebb. Between deployments 1 and 2 (pre- and postdredge), the axis of the flood/ebb currents at the west station in the Nahcotta Channel rotates by approximately 14 deg clockwise, but there is only a minor change in ebb and flood speeds.

At the middle station there is a 10 cm/sec reduction in both ebb and flood speeds between the predredging deployment and the postdredging deployments. Changes in current direction at the middle station and in current speed and direction at the east station appear to be insignificant from predredging to postdredging deployments.

Figure 3-50 shows the cross-correlation as a function of lag between the along channel velocity component V_x at 0.35 m above the bed, and SSC at 0.35 m and 1.14 m above the bed. The cross-correlations include data over a period of about 700 hr of measurements at the middle station during the second deployment.

Table 3-4
Comparison of Ebb and Flood Current Speeds and Directions

Maximum Depth-Averaged Current Speed for Flood and Ebb Phases						
Speed (cm/sec)	West Nahcotta Channel		Middle Bay Center Entrance		East Bay Center Entrance	
	Flood	Ebb	Flood	Ebb	Flood	Ebb
Deploy 1	98.1	58.4	57.7	86.3	29.2	56.9
Deploy 2	93.8	56.3	54.0	76.7	26.7	57.1
Deploy 3 (1st half)	N/A	N/A	50.2	75.5	25.2	54.4
Deploy 3 (2nd half)	N/A	N/A	48.7	74.6	25.5	54.2

Direction of Maximum Depth-Averaged Current Speed for Flood and Ebb Phases						
Direction (deg)	West Nahcotta Channel		Middle Bay Center Entrance		East Bay Center Entrance	
	Flood	Ebb	Flood	Ebb	Flood	Ebb
Deploy 1	185.0	359.4	77.0	256.9	67.4	243.3
Deploy 2	198.6	14.2	72.3	253.9	64.6	250.0
Deploy 3 (1st half)	N/A	N/A	70.5	252.9	67.1	250.4
Deploy 3 (2nd half)	N/A	N/A	71.4	254.3	67.5	250.6

Cross-correlations between V_x and SSC are generally much higher than between V_y and SSC. The cross-correlations indicate that peaks in SSC occur before peak flood current speeds in V_x and after the peak ebb current speeds at the middle station. The peak SSC occurs up to 5 hr before the peak flood current speed and 1 to 2 hr after the peak ebb speed at 0.35 m above the bed. This latter peak coincides with the ebb slack and is also therefore coincident with the large, short-term increases in bed elevation observed in Figure 3-42.

The peak SSC follows the peak in ebb current speed by up to 5 hr and preceeds the peak flood speed by 1 to 2 hr at 1.14-m elevation. This phase difference suggests that a significant portion of the SSC observed at the middle station may not be due to locally derived suspension, but may be advected from upstream sources in the Palix River or derived from resuspended sediments on the adjacent tidal flats.

Figure 3-51 shows times series of water depth above the current meter and suspended sediment flux computed as the cross product of measured velocity and SSC at 0.35 m. The fluxes are clearly bidirectional in the channel, with the majority of the flux occurring during the ebb (negative flux in Figure 3-51). Across-channel fluxes are predominately southward (negative flux in Figure 3-51), but minor in comparison with the along-channel fluxes.

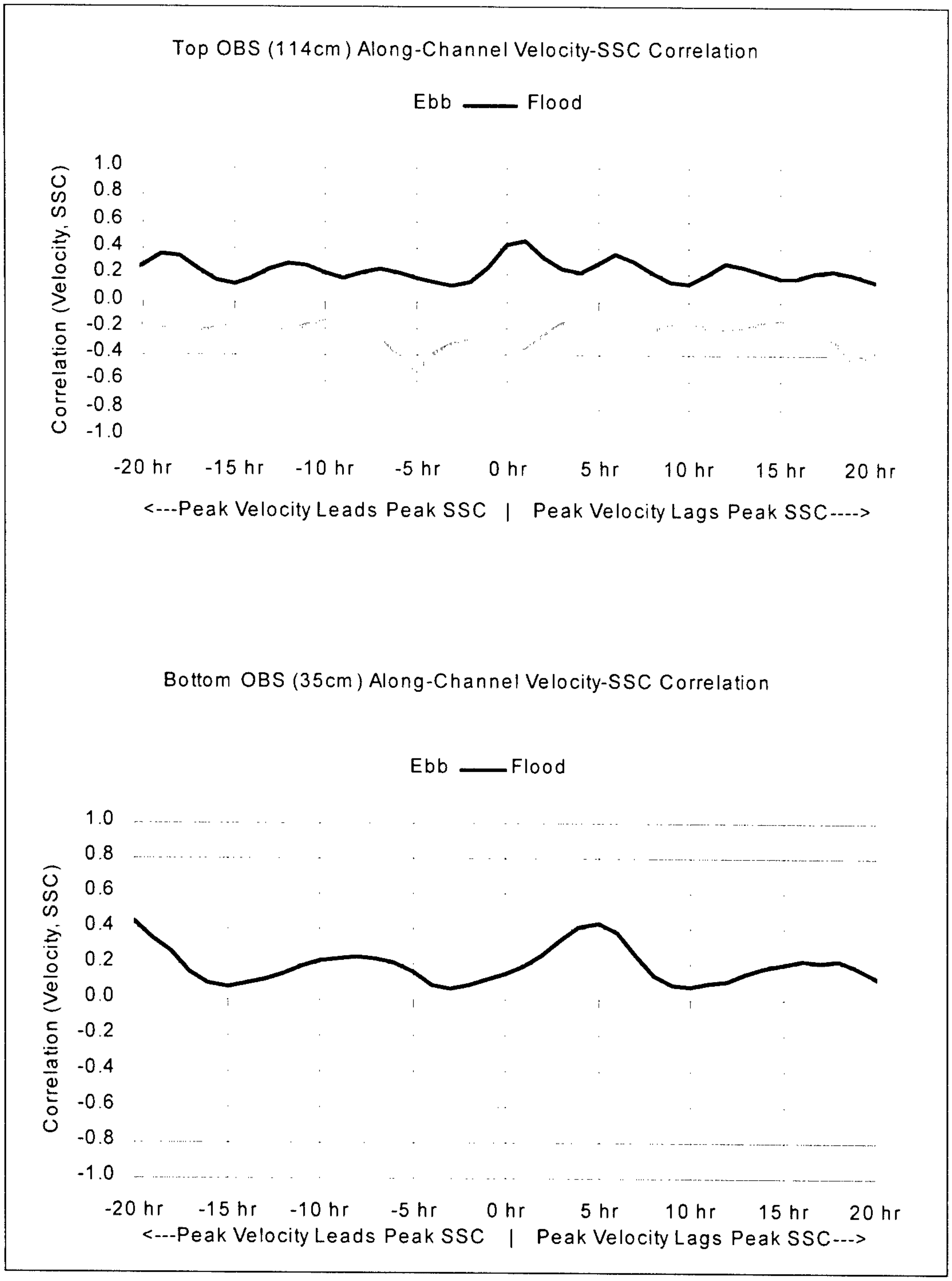


Figure 3-50. Cross-correlation between SSC at 1.14 m (upper) and 0.35 m (lower) and V_x as a function of lag for upper and lower OBS at middle station during deployment 2

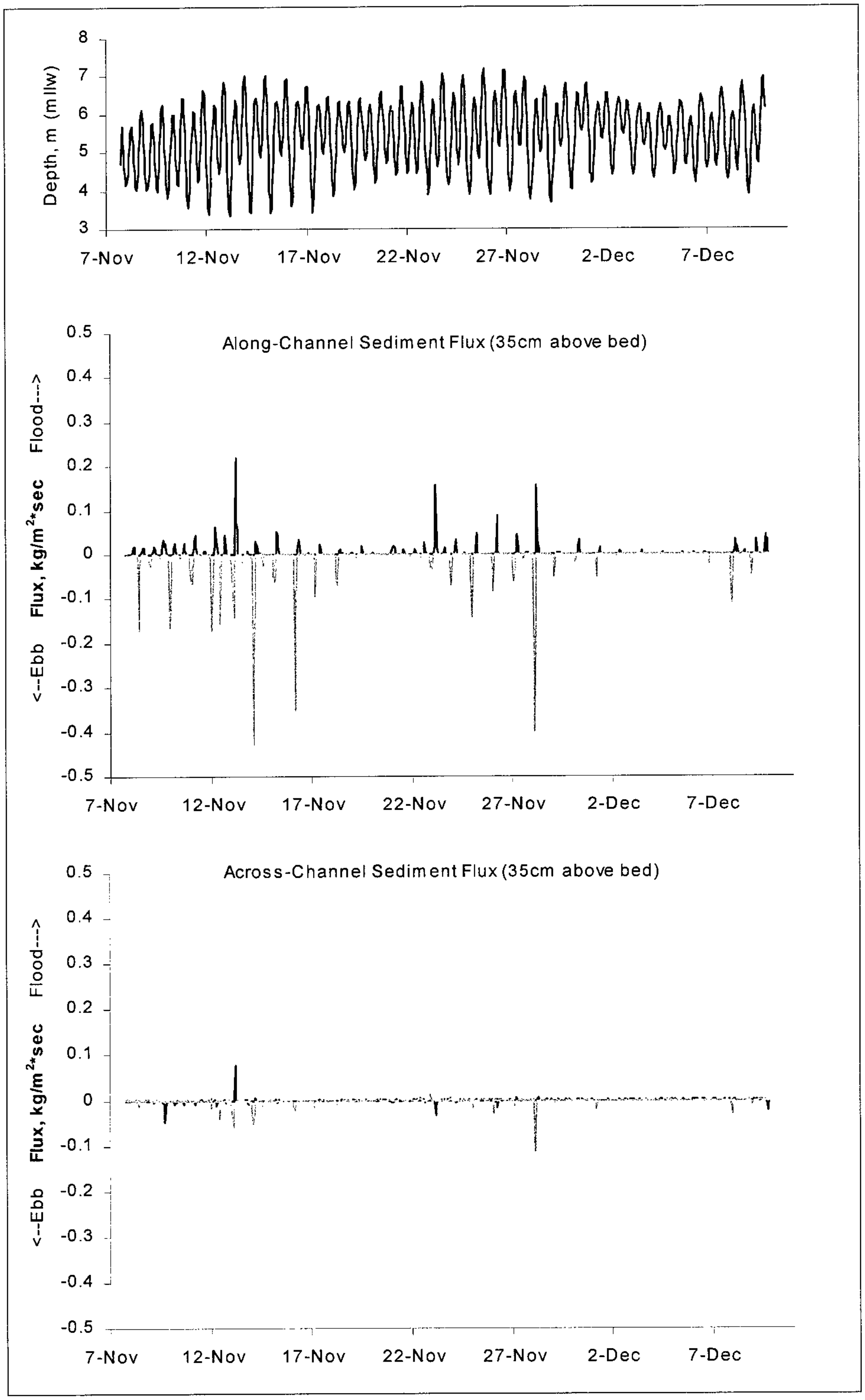


Figure 3-51. Times series of water depth and the instantaneous suspended sediment flux computed as the product between SSC at 0.35 m and V_x (middle graph) and SSC and V_y (lower graph) at middle station during deployment 2

Summing the instantaneous fluxes over time provides an indication of the relative contributions to the gross suspended sediment flux. Total fluxes are expressed as percentages and summarized in Table 3-5.

Table 3-5
Percentage Total Suspended Sediment Flux

	Z = 0.35 m (percent)	Z = 1.14 m (percent)	Depth-averaged (percent)
Flood (Along Channel)	31.0	46.8	34.6
Ebb (Along Channel)	56.5	40.4	52.8
Flood (Across Channel)	4.0	6.5	4.5
Ebb (Across Channel)	8.5	6.3	8.0

More than 50 percent of the gross suspended sediment flux in the lower water column is associated with the along-channel ebb. The across-channel components of flux are minor in comparison with the along-channel components. The depth-averaged across-channel flux during the ebb in the lower water column is approximately twice as large as the across-channel flux during the flood. At higher elevations, the fluxes are more equally proportioned between ebb and flood.

Discussion

At the west station, situated on the eastern edge of Nahcotta Channel and near the mouth of Bay Center Entrance Channel, the currents are flood-dominated. Current direction is more variable during ebb phases than flood phases at this location. The phase difference in direction variability is apparent throughout the water column. The predominant current is south-southwest during the flood, turning clockwise to the north-northeast at the end of the flood. Current on the ebb shifts from northeast to the east, then back to the north-northeast. This clockwise evolution in current direction suggests a southward drainage of the adjacent tidal flats and corresponds with an observed southward migration of the north channel shoal determined from aerial photography and bathymetric surveys.

Variability in the vertical structure of current direction during the ebb in the Nahcotta Channel is presumably associated with the convergence of flows from Nahcotta Channel and those exiting Bay Center Entrance Channel. The contrasting flood and ebb dominance between Nahcotta and Bay Center Entrance Channels, respectively, implies that a transition zone exists between the west and middle stations.

The combination of a strong but decelerating ebb current in Bay Center Entrance Channel converging with a weak ebb current on the east side of Nahcotta Channel, together with a steep increase in depth at the channel confluence, permits expansion and lateral spreading of flows from Bay Center. Convective and advective decelerations create a depositional node for the high sediment load being carried by the ebb flow from Bay Center Entrance Channel and are a possible mechanism for the shoaling at the location requiring frequent maintenance.

The maximum SSC at 1.14-m elevation occurs just after the maximum current speed on the flood and somewhat later on the ebb. Near the bed, the maximum SSC coincides with low water and ebb slack. Ensemble-averaged H_s exhibits a rapid increase during the latter stages of the flood, reaching a maximum at high tide, and followed by a less rapid decrease as the tide falls. Bed levels exhibit a maximum just after the start of the flood, following the near-bed peak in SSC at ebb slack. A rapid decrease in bed level suggests most of the newly accreted sediment is again remobilized during the flood phase. There is a slight deposition again at high tide, followed by pronounced erosion again on the ebb. The close correlation of the maximum SSC at 1.14-m elevation with both the peak ebb and flood currents indicates that a portion of the sediment suspension is due, at least in part, to the local tidal current-induced bed shear stress.

The high SSC near the bed at ebb slack indicates that just prior to slack, there is a significant quantity of sediment suspended to heights greater than 0.35 m above the bottom. This coincidence of maximum SSC near the bed with minimum horizontal velocity results from the settling of sediment suspended higher in the water column during the ebb.

Approximately 53 percent of the gross suspended sediment flux is associated with the along-channel ebb, while approximately 35 percent occurs on the flood. Across-channel fluxes are minor in comparison with along-channel fluxes. This, together with the interpretation of the cross-correlation lags, suggests that sources of a significant portion of the suspended sediments observed in the ebb flow are distant from the measurement location. Other sources may include the advection of a turbid fringe created on adjacent tidal flats by wind waves at high tide, advection of upstream sediments suspended by channel hydraulics, and/or fluvial sources derived from the Palix River. The existing data cannot conclusively identify the ultimate source of the sediment observed in Bay Center Entrance Channel.

Interpretation of Bay Center Entrance Channel Bathymetric and Hydrodynamic Change

Sediment moving along the eastern bank of the Nahcotta Channel was expected to deposit in the outlet of the Northwest Channel, but that is not evident from survey comparisons. Deposition on the South Bank shoal at the eastern edge of Nahcotta Channel and the southern bank of the Northwest Channel indicates that sheet flow that was once transported sediment on the surface of the shoal has been captured by the dredged channel. Sediment, in transport under the influence of waves on the shoal, is no longer removed by sheet flow, and has

accreted on the shoal. Deposition at the connection of the East-West and the Northwest Channels can be interpreted as resulting from sediment moving along the Main Channel Spit on the northern side of the East-West Channel, and dropping out of the flow at the inside of the bend made by the two segments of the channel. Bay Center Entrance Channel, at both Sections A and B, maintained authorized project dimensions, through 20 December 2000. Examination of Figures 3-34 and 3-35 indicates that the channel width-depth ratio adjusted, and the channel location translated southward throughout the monitoring period. Tables 3-2 and 3-3 show net deposition at Section A in the 0- to 8-ft depth range, and minor erosion, mainly in the 4- to 8-ft depth range at Section B.

Comparison of channel surveys dated 1983 to 2000 reveal a pattern of seasonally alternating locations of channel shoaling and shifting at the dogleg portion of the channel, or the junction of the main East-West Channel and the Northwest Channel. That area experiences the heaviest shoaling. A sequence of surveys of the Bay Center Entrance Channel dated 14 November 2000 through 15 May 2001 is presented in Figures 3-20 through 3-26. For reference, the dredging footprint recommended in 2000 is shown on the bathymetry of each date.

During the summers in years prior to 2000, the channel appeared to follow a pattern of deepening (or at least decreasing its rate of shoaling) and moving to the northeast, as represented by the survey of 24 August 1999 and 14 September 2000. From late summer through fall the channel appeared to be in transition to relocating southwestward, as shown by the survey dated 7 November 1998.

Postdredging surveys indicate that in the period November through December 2000, the channel filled on the north side at the dogleg portion, shoaled slightly in the channel bottom, and shifted toward the south. That process accelerated between the survey dates 20 December 2000 and 15 May 2001. Later surveys will show whether the channel shifts northeastward again.

Measurements of the current, waves, and water level made at three stations in Bay Center Entrance Channel during the period preceding and immediately following dredging span the season in which the channel has been observed to change location. The measurements are interpreted with the morphology changes to specify processes that are responsible for the observed pattern of channel changes. The time variation in suspended sediment concentration and bottom level, together with the current phasing, yields an explanation of channel sediment dynamics.

Currents in the channel are dominated by the along-channel component of velocity. At the middle and east stations, currents were flood-dominated prior to dredging. After dredging, currents at those stations are ebb dominated. The cross-channel component of the currents is minor, and of that component, the southerly direction dominates (at locations on the north side of the channel). This flow asymmetry indicates that after dredging, there is a net migration of sediment toward the northwest, or to Nahcotta channel. Sediment is suspended on the tidal flats by wave action at high tide. At the start of the ebb, suspended sediment on the tidal flats begins to flow toward the channel. As the ebb current increases, sediment that accumulated at upstream locations begins to mobilize. At the peak of the ebb velocity in the channel, the bed sediments in the channel are mobilized and transported toward Nahcotta Channel. The bed elevation in

Bay Center Entrance Channel lowers as much as 10 cm during ebb peaks in the spring tide series. The peak in the suspended sediment load is advected past east and middle stations after the ebb velocity has peaked and is decelerating. At the time the ebb current at the location of the middle station reaches a maximum, the ebb current at the west station at Nahcotta Channel has already begun to decelerate. The decelerating flow field promotes sediment deposition, as indicated by the observed deposition on the bed near the time of low water slack, and is the likely mechanism responsible for the persistent shoaling at the dogleg portion of the Bay Center Entrance Channel. The confluence of Bay Center Entrance Channel and Nahcotta Channel (west station) is flood-dominated and the postdredge channel (middle and east stations) is ebb-dominated. This combination creates a convergence at particular phases of the tide when the suspended sediment load is greatest at the location between the west and middle stations, thus contributing to sedimentation in the vicinity of the shoal.

Prior to the maintenance dredging in October 2000, the peak of the tidal current speeds at the west station preceded the peak at the middle station. This phase difference can be understood by considering the west station is in deeper water and the tide curve is relatively unaffected by channel constrictions. The middle station, near the shoaled portion of the channel, experiences a tidal regime that is affected by the shoaled bottom before it was dredged. The constriction of the shoaled channel reduces the volume of tidal exchange upstream of the shoaled area and delays the peak of the ebb current until later in the tidal cycle when the head difference between the upstream water-surface elevation and that downstream is maximum. The postdredge configuration allows a freer exchange of tidal flows. Without the shoal deforming the tide curve in the channel, the current peaks in response to the tidal wave and the freshwater discharged to the system upstream of the middle station, resulting in a peak current that precedes that at the west station.

The pattern of channel shifting southward during the winter repeated in the 2000-2001 winter, despite the recently dredged dimensions and improved hydraulics. The persistence of this pattern of channel movement to the south in the winter (and presumably the return to a more northern location next summer) indicates that seasonally dominated processes are controlling the deposition, erosion, and channel hydraulics. Upland drainages tributary to Bay Center are dominated by winter runoff and sediment delivery. The amount of freshwater discharge is an unknown component of the total flow in Bay Center Entrance Channel, but the sediment loads and transport power of the currents in winter are greater than in summer. In winter, the channel was observed to divide and develop a major channel to the south of the summer channel position. During the summer the channel reoccupies the same location as the year previously. The depth of the channel appears to depend on its previous history (recent dredging), intensity of channel meandering, and sedimentation during the previous winter. Dredging is most efficient during the summer and in the stable summer alignment. Dredging improves the likelihood that the channel depth, upon return to the previous year's location, will be near the project depth.

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4 Willapa Entrance and Bay Center Entrance Channel Numerical Modeling[1]

This chapter describes circulation and sediment transport calculations conducted for the entrance to Willapa Bay and for Bay Center, Washington. Sediment transport models have been implemented that calculate change in bottom elevation over time. Circulation modeling and a sediment transport analysis conducted for the entrance to Willapa Bay is first described, and then circulation and sediment transport modeling performed for Bay Center Entrance Channel is presented. This sediment transport model was applied at Bay Center because it was feasible to obtain comprehensive process and response data there, and because morphological changes are clearly apparent as channel migration. Thus, Bay Center provides an evaluation area for the model in which its predictive capabilities can be assessed.

Willapa Bay Entrance

Circulation modeling of the Willapa Bay entrance was conducted as an extension of the original work described in Report 1 (Militello et al. 2000). The goal of this extended modeling is to relate the hydrodynamics and sediment movement that occur at the entrance. This section describes circulation modeling for the year 2000 and an analysis of sediment transport for 1998 and 2000.

Circulation modeling

Water level and current velocity modeling at the entrance to Willapa Bay was conducted with the model ADvanced CIRCulation (ADCIRC) (Luettich, Westerink, and Scheffner 1992). The modeling was based on the effort conducted for the initial navigation feasibility study (Report 1). In that work, a regional ADCIRC mesh was developed that specified detailed resolution at the Willapa Bay entrance. Bathymetry from 1998 surveys that covered much of the entrance and bay were applied. Details of the mesh, model validation, and simulations from the initial effort are given in Militello et al. (2000). The original ADCIRC mesh and the archived simulations provided a basis for

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comparison of change in bathymetry from July-August 1998 (noted herein as summer 1998) to March-May 2000 (noted herein as spring 2000) and change in circulation patterns and current speed.

For comparison of hydrodynamics over the 2-year interval from 1998 to 2000, the ADCIRC mesh that contained the 1998 bathymetry was updated with survey data collected in spring 2000. These soundings were made in the northern portion of the entrance. No other changes were made to the mesh so that the 1998 and 2000 simulations could be compared. Figure 4-1 shows the ADCIRC mesh for Willapa Bay, and Figure 4-2 displays detail of the mesh in the entrance.

Simulations for both 1998 and 2000 were conducted for time intervals in 1998 so that direct comparisons between currents and flow patterns could be made. A plot of calculated and measured water level at the Toke Point NOS gauge is shown in Figure 4-3 for the time interval 5 September to 4 October 1998 (day of year 248 to 278). The calculated tide range matches the measured range well for most of the monthlong simulation. During some time intervals, such as day of year 253 through 258, high-water values are overpredicted and low-water values are underpredicted. This error may owe to nontidal processes that are captured by the measurements, but are not calculated by the model, or inaccuracies in the tidal constituent specifications at the open boundary of the ADCIRC model.

Depths contained in the 1998 and 2000 meshes are shown in Figures 4-4 and 4-5, respectively, referenced to mean tide level (mtl). Over the 2-year interval, the North Channel became deeper and wider in the vicinity of the SR-105 structure. In addition, the shoal that was present at the seaward end of the North Channel during 1998 was breached, leaving a deeper area in the 2000 bathymetry.

The change in depth at the entrance from summer 1998 to spring 2000 is shown in Figure 4-6. In this figure and all others containing elevation or depth change, yellow and red areas denote accretion and blue areas denote erosion. Templates of the channels that had greatest ranking in the initial feasibility study, Alternatives 3a and 3Ha, are shown, as well as that for Alternative 1, which was the existing channel in 1998. Deepening has occurred over the length of the Alternative 3a alignment, which is in agreement with the model calculations in Report 1. Depth has increased over the eastern half and western third of the Alternative 3Ha template, and shoaling has occurred between these areas. The shoaling is located at the S-curve in the Alternative 1 channel. This shoaling and the deepening on the eastern portion of the channel are in agreement with the findings of Report 1. The area of apparent accretion to the northwest and north of the seaward extent of Alternative 3a is an artifact of the mesh development. For the 1998 mesh, survey data for that area were not available, so depths had to be estimated. The 2000 survey collected soundings over that area. Error in approximation of the 1998 bathymetry gave unrealistic values for change in depth in that limited area over the 2-year interval.

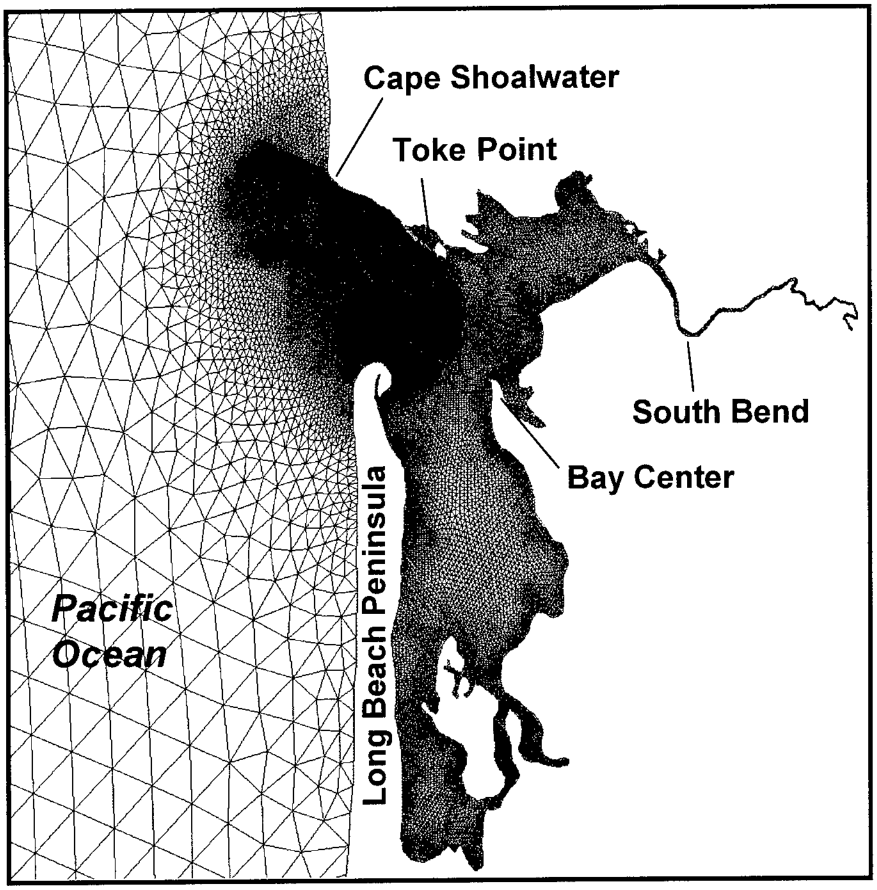


Figure 4-1. Mesh of Willapa Bay developed for detailed calculations in entrance

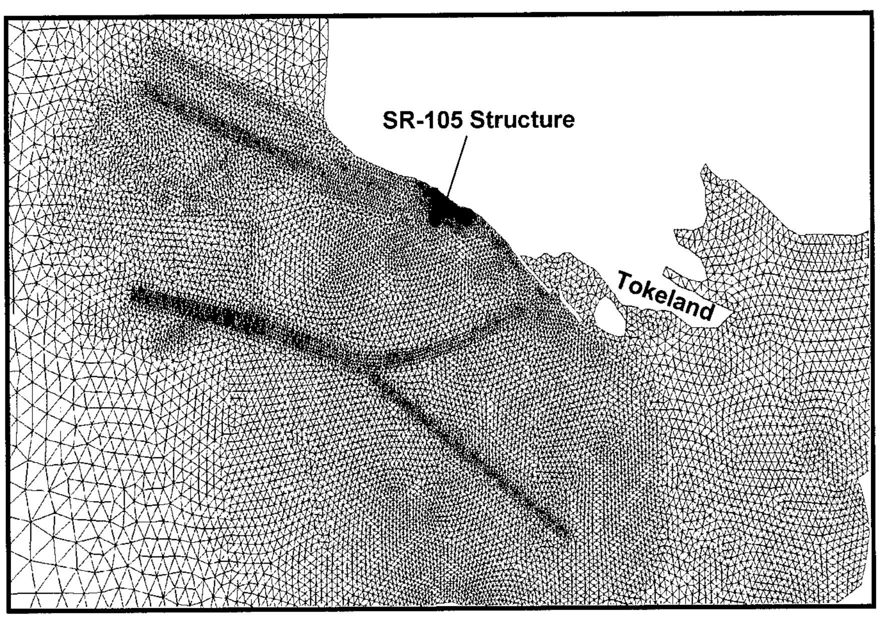


Figure 4-2. Mesh detail of Willapa Bay entrance

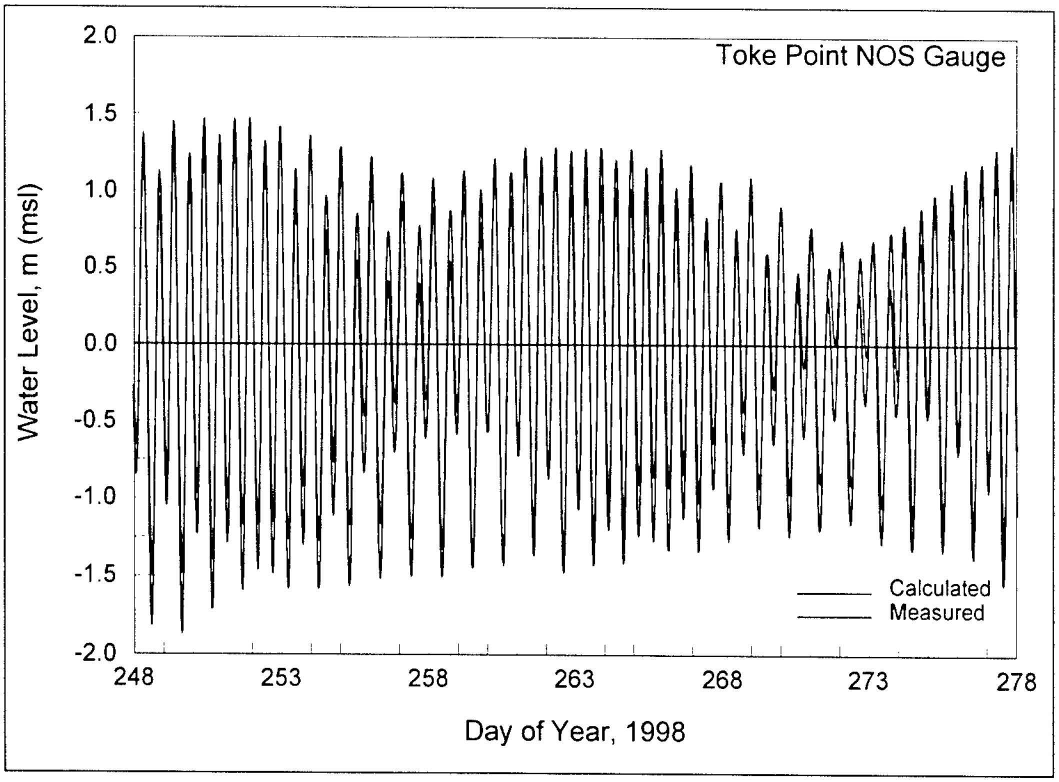


Figure 4-3. Measured and calculated water level at Toke Point, 5 September to 4 October 1998

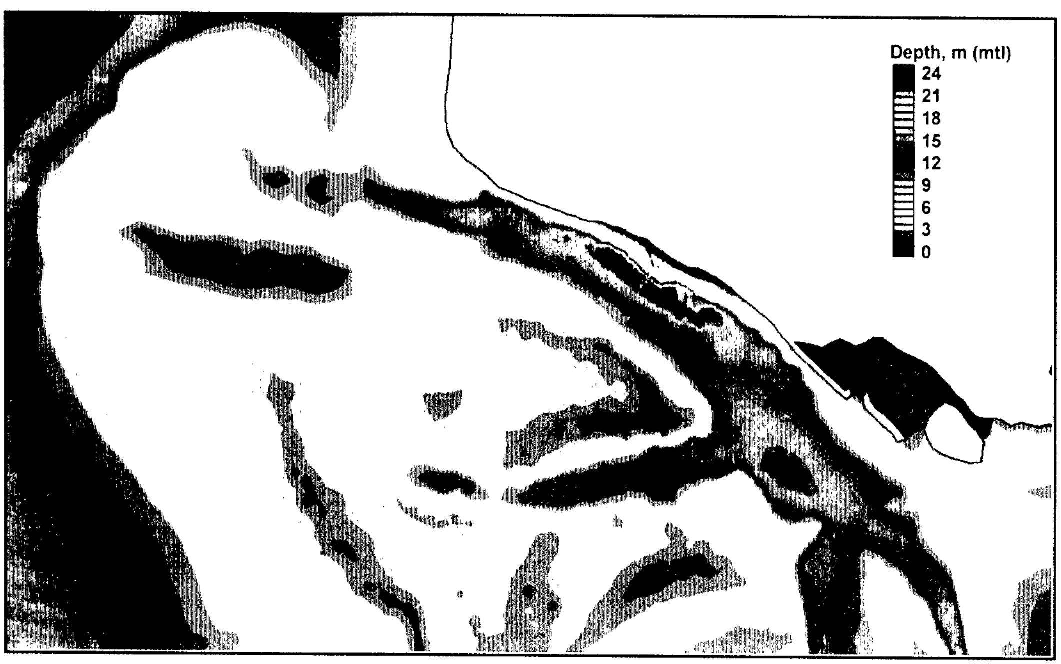


Figure 4-4. Willapa Bay entrance bathymetry, summer 1998

Figure 4-5. Willapa Bay entrance bathymetry, spring 2000

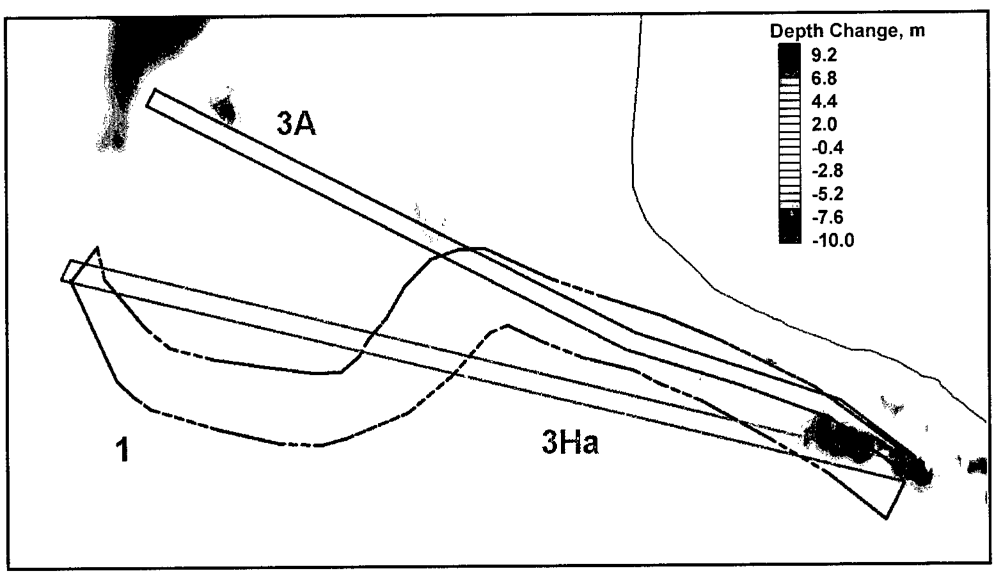


Figure 4-6. Change in bottom elevation from 1998 to 2000

Significant differences in the bathymetry from 1998 to 2000 are a deepening and widening of the North Channel apparently in response to the construction of the SR-105 structure, and the formation of a channel through the northwestern ebb tide shoal, extending directly from the North Channel. Details of the bathymetry change are described in Chapter 3.

An area of erosion occurred on the outer edge of the ebb shoal to the south of the Alternative 3a alignment (along the middle left edge of Figure 4-6). In this area material probably moved onshore in response to wave stresses once the 1998 channel moved to the north and no longer provided sediment to this area on the ebb currents. This material may have been deposited in the S-curve of the 1998 channel landward of the erosion. Other primary areas of depth change occurred within the North Channel in the vicinity of the SR-105 structure. Along the northern edge of the channel deposition took place, presumably in response to the protection the structure provided to that shoreline. Significant erosion in the center of the North Channel took place in response to the greater velocities in the channel owing to the presence of the SR-105 structure. Erosion in this area exceeded 10 m in places. Deposition also took place along the southern edge of the North Channel in the same area, owing to migration of Deadman Island.

Simulations were conducted with the 2000 bathymetry to examine the current strength and patterns and to compare them with the simulations conducted with the 1998 bathymetry. To facilitate comparisons between the two sets of bathymetry, three simulations with the 2000 bathymetry were conducted. These simulations are identical to those for the existing condition described in Report 1, with the exception that the bathymetry has been updated. The three simulations are: forcing with tide only, forcing with tide and fair weather waves, and forcing with tide and storm waves. The fair weather waves are given in Table 5-7 in Report 1 (Smith and Ebersole 2000). The storm waves are for the January 1998 storm starting on 13 January, and these wave parameters are also described in Report 1.

Plots of current patterns for the situation of forcing only by tide, and with the 2000 bathymetry are shown in Figures 4-7 and 4-8 for peak ebb and peak flood, respectively. During ebb, the strongest velocity occurs in the North Channel, and weakest velocity is located over the shallow areas of the entrance. During flood, strong currents occur both in the North Channel and in a shallow conduit located on the southern portion of the entrance. Because the tidal current at the entrance is significantly modified by the presence of waves, further discussion of calculated currents at the entrance will be focused on forcing by waves and the tide.

Representative current patterns and strength for peak ebb and peak flood for the 1998 bathymetry are shown in Figures 4-9 and 4-10, respectively, and for the 2000 bathymetry in Figures 4-11 and 4-12, respectively. Little change in current patterns occurred over the 2-year interval. However, the changes in bottom topography did modify the current strength. Figures 4-13 and 4-14 show contours of representative change in speed at peak ebb and peak flood flow, respectively. Yellow and red shades denote increased speed and blue shades denote decreased speed. During peak ebb, the current in 2000 was stronger than

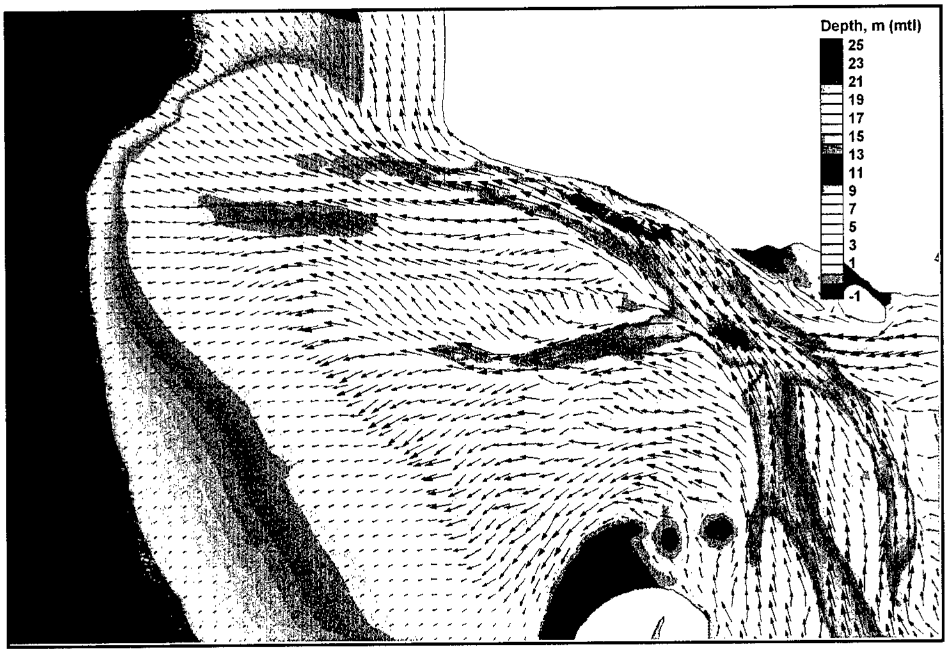


Figure 4-7. Current patterns at peak ebb flow, spring 2000 bathymetry, tide forcing

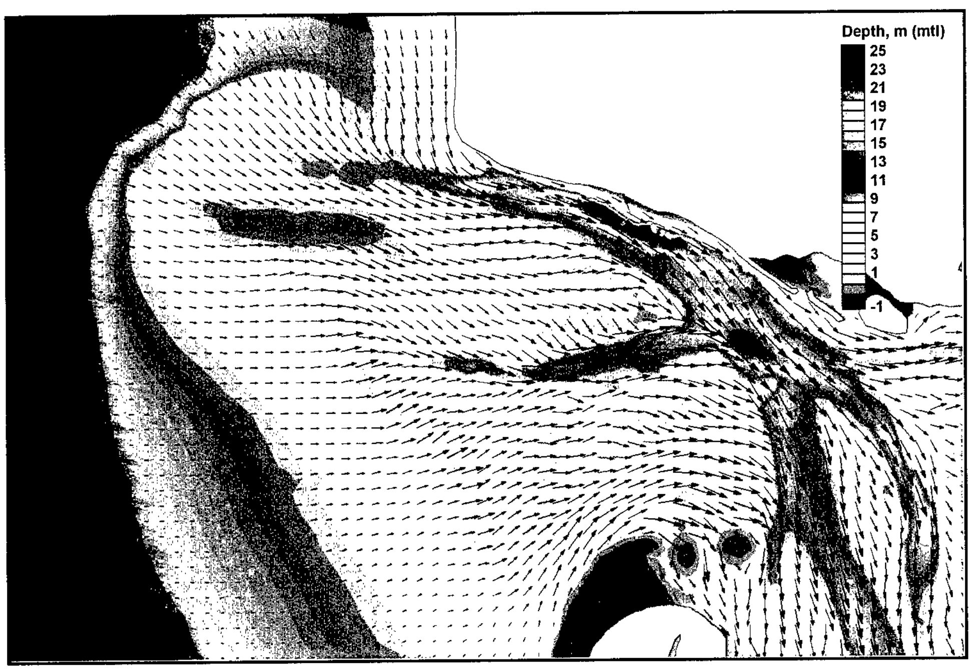


Figure 4-8. Current patterns at peak flood flow, spring 2000 bathymetry, tide forcing

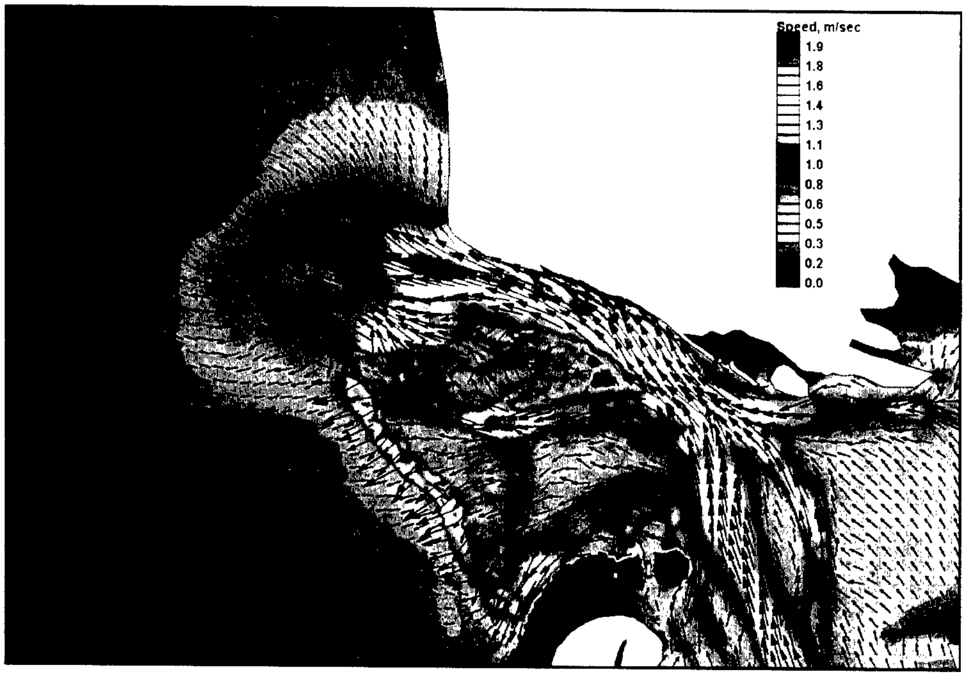


Figure 4-9. Peak ebb current at Willapa entrance, 1998 bathymetry, tide and wave forcing

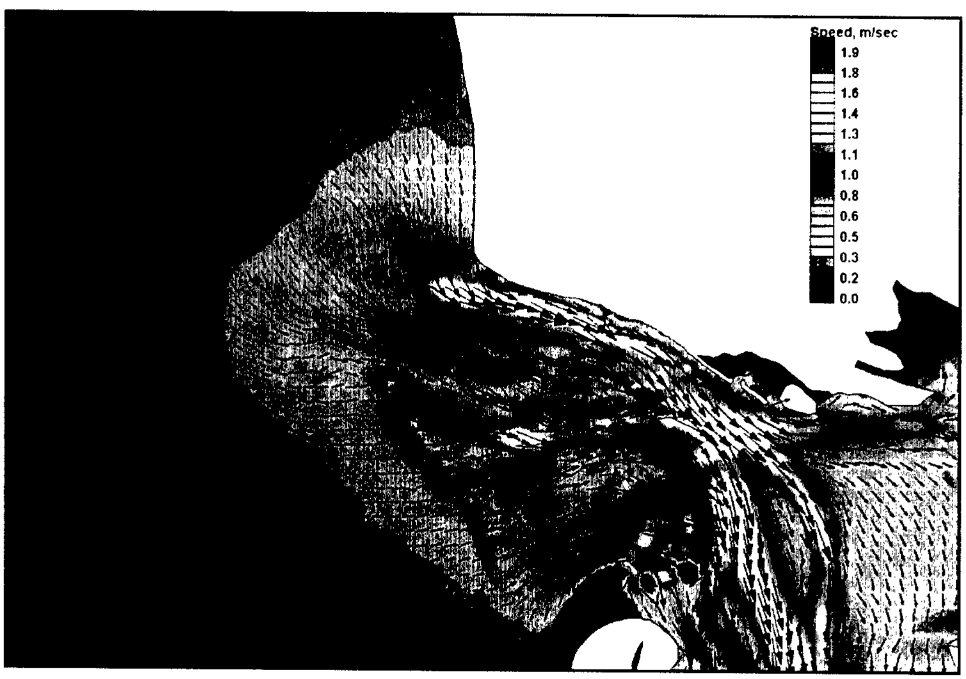


Figure 4-10. Peak flood current at Willapa entrance, 1998 bathymetry, tide and wave forcing

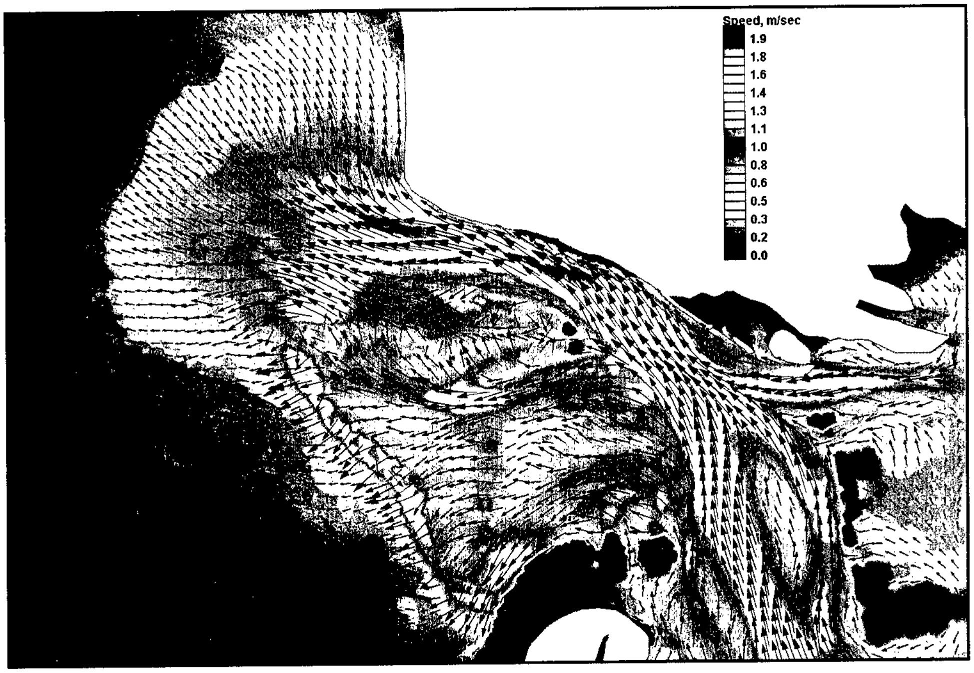


Figure 4-11. Peak ebb current at Willapa entrance, 2000 bathymetry, tide and wave forcing

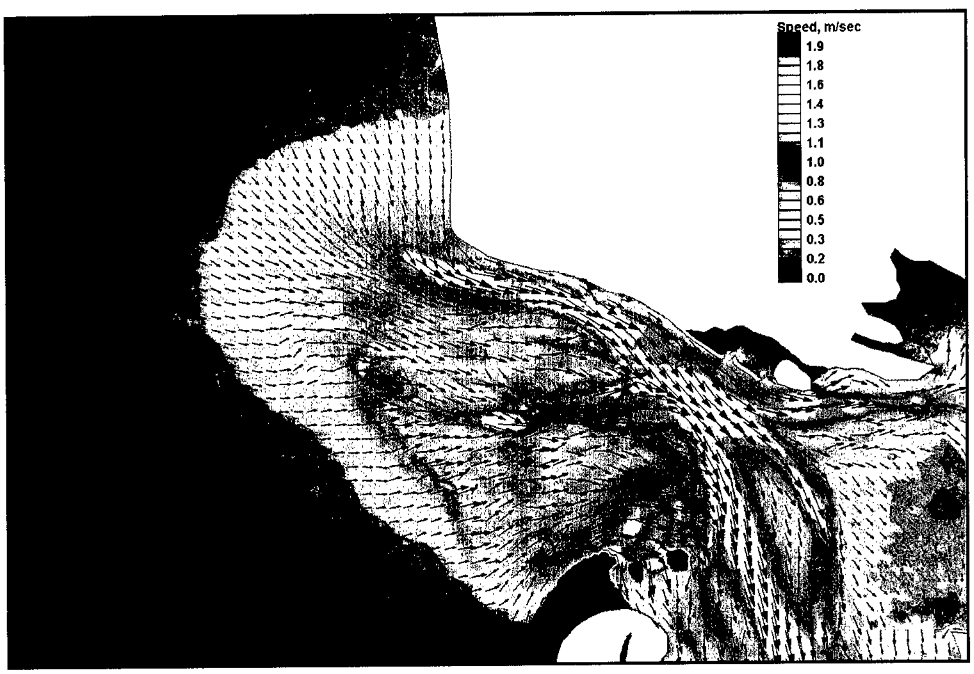


Figure 4-12. Peak flood current at Willapa entrance, 2000 bathymetry, tide and wave forcing

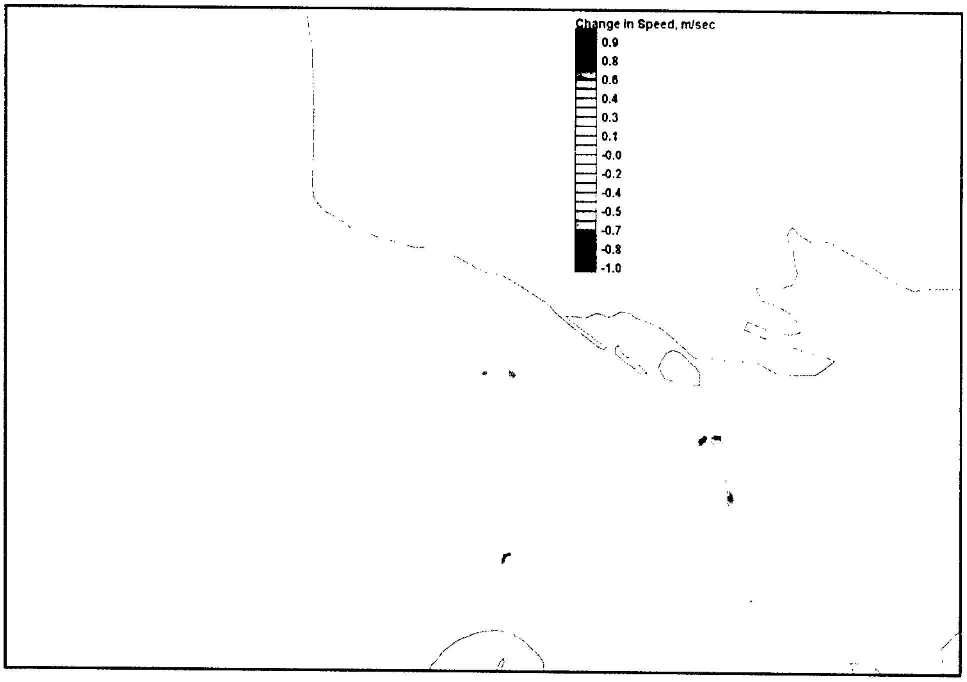


Figure 4-13. Change in current speed from 1998 to 2000, peak ebb

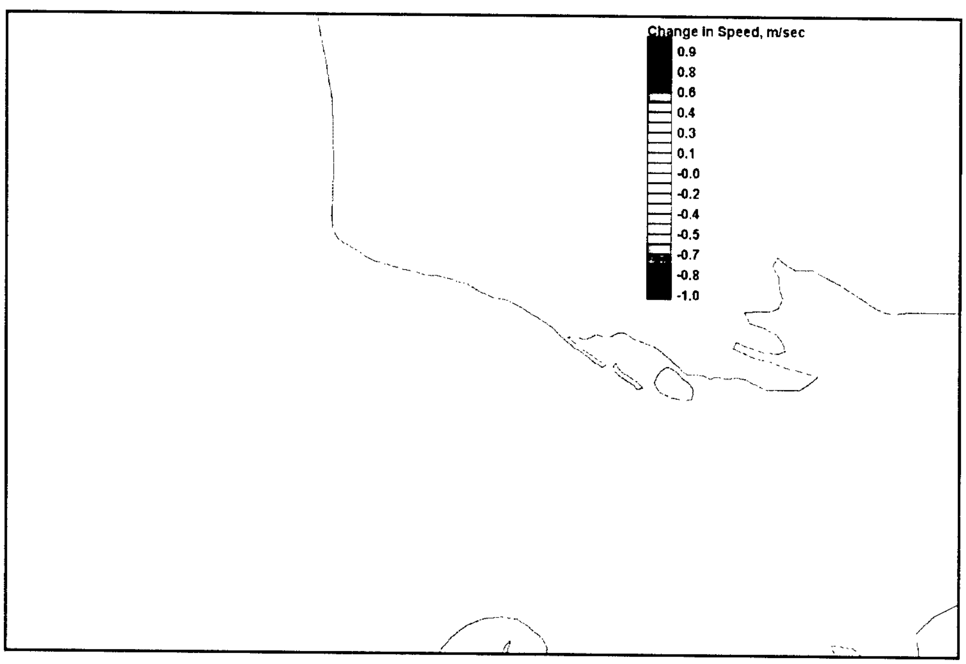


Figure 4-14. Change in speed from 1998 to 2000, peak flood

in 1998 for the North Channel and the outer North Channel area. Increases in speed over this area ranged from near zero to approximately 0.45 m/sec at the SR-105 structure. At the outer portion of the North Channel, the speed increased by a maximum of approximately 0.4 m/sec. At peak flood current, speed was decreased over much of the entrance, although it was increased near the SR-105 structure. Comparison of change in speed at peak ebb and peak flood indicates a shift to stronger ebb dominance in the North Channel, promoting a continuation of channel self-maintenance over much of its length. Changes in speed inside Willapa Bay shown in Figures 4-13 and 4-14 may owe to slight modifications in tidal phase from 1998 to 2000. Because of the deepening of the North Channel over the 2-year interval and its trend toward greater ebb dominance, the tidal phase inside the bay can be altered, leading to an apparent change in speed at a snapshot in time.

Sediment transport calculations at Willapa entrance

The regional ADCIRC modeling conducted for this study was applied, in part, to provide current fields for the Willapa Bay entrance channel area for calculation of sediment transport. The velocity fields applied for the sediment transport calculations were computed for three situations, tide forcing, tide and fair-weather wave forcing, tide and storm wind and wave forcing. To reduce the large ADCIRC velocity solutions to a manageable size and to provide a regularly spaced solution set for sedimentation analysis, the ADCIRC mesh depths and current fields were interpolated to a Cartesian grid. The grid contains 90 cells along the east-west axis and 60 cells along the north-south axis, with a regular cell size of 0.0015 deg (approximately 500 ft).

To quantitatively evaluate the potential sedimentation processes and patterns in the Willapa entrance, a procedure was developed to predict locations of scour or deposition from the ADCIRC-calculated velocity field time-histories. A sediment total-transport algorithm was developed to calculate the time variation in depth (or bottom elevation) on the Cartesian grid by application of the ADCIRC-calculated velocity fields. The sediment total-transport formulation applied for change in bottom elevation over time is (Watanabe 1987):

$$\frac{\partial z_b}{\partial t} = -\frac{\partial}{\partial x}\left(q_x - \varepsilon \left| q_x \right| \frac{\partial z_b}{\partial x} \right) - \frac{\partial}{\partial y}\left(q_y - \varepsilon \left| q_y \right| \frac{\partial z_b}{\partial y} \right) \qquad (4\text{-}1)$$

where

z_b = is the bottom elevation

q_x = is the x-directed sediment transport rate

ε = is an empirically-derived coefficient taken here to be 10

q_y = is the y-directed sediment transport rate

The terms containing the spatial variation in the bottom elevation represent material that moves down the face of a slope. The directional transport rates q_x and q_y are given by:

$$q_x = A_0 \frac{(\tau - \tau_{cr})u}{\rho_w g} \tag{4-2}$$

and

$$q_y = A_0 \frac{(\tau - \tau_{cr})v}{\rho_w g} \tag{4-3}$$

where

A_0 = is a nondimensional coefficient taken here to be 0.5

τ = is the maximum value of the bottom shear stress

τ_{cr} = is the critical shear stress taken here to be 0.05

u and v = are the components of velocity parallel to the x and y axes, respectively

ρ_w = is the density of water, and g is the acceleration due to gravity

The maximum bottom shear stress τ is:

$$\tau = C_{b\_\max} \rho_w U^2 \tag{4-4}$$

where

$C_{b\_\max}$ = the maximum bottom-friction coefficient

U = the total current speed

The sediment transport calculations were conducted in a postprocessing mode on the ADCIRC-calculated velocity fields. Because the velocity data was calculated by ADCIRC prior to application of the sediment transport algorithms and depth-change calculations, the updated depths were not fed back into the velocity calculations. For the sediment transport analysis, this type of feedback could create stability problems because it would upset the natural balance of velocity for a given water depth. As depths change with erosion or deposition, the ADCIRC-calculated velocities do not change, eliminating the natural feedback mechanisms that prevent shoaling in areas where velocities normally increase in response to decreasing depths. To compensate for change in depth by the sediment transport calculations, velocities were modified in response to depth change so that the total flow was maintained into and out of each cell. This adjustment was made by multiplying the original ADCIRC velocity at each cell by the ratio of the original depth to the new updated depth, to obtain a modified velocity for the subsequent sediment transport calculation. The modified velocity also maintains flow continuity at each cell.

In addition to the change in bottom depths, the sediment motion calculations have also been applied to help visualize net sediment movement pathways. The procedure consists of summing the sediment movement velocity vector at each calculation time-step over the sedimentation analysis time period. The sign of the vector is preserved in the summing so that positive sediment movement (along an axis on the grid) offsets negative sediment movement as the tidal

currents ebb and flood over each tidal cycle. The sum of the sediment movement vectors is an indicator of the net current-driven sediment motion at each cell location, and is referred to here as sediment movement vectors.

Vectors plotted in Figures 4-15 and 4-16 show the current-driven sediment pathways across the Willapa entrance for 1998 and 2000, respectively. Comparison of the 1998 and 2000 pathways indicates that, in general, the sediment movement is similar for the two time periods. One area of difference is the northwestern edge of the North Channel. At this location, the pathways are directed toward the northwest in the year 2000, as opposed to a more westerly direction in 1998. This change owes to the breaching of the northwestern portion of the ebb shoal.

The net transport tends to move sediment in over the outer shoal areas along the central portion of the entrance, and out through the North Channel and northern shoal areas. Movement of sediment across the shallow interior shoal areas is irregular because it is forced by the combined action of tidal and wave-driven currents.

The results of the sediment transport analysis are shown in Figures 4-17 through 4-20. Calculated depth changes for a month-long simulation with currents forced by tides are shown for the 2000 bathymetry condition in Figure 4-17. In order to make comparisons between simulations of various lengths and between simulations and bathymetric surveys, the depth changes have been normalized into daily rates. For this case with forcing by typical tidal and fair–weather wave-driven currents, the maximum depth changes are in the range of 0.02 m/day.

As a check on the reasonableness of the depth change simulation technique, Figure 4-17 can be compared to Figure 4-18, where the actual measured depth changes from 1998 to 2000 have been normalized and plotted in the same manner as the calculated values. The maximum observed depth changes are slightly less than 0.02 m/day (about 10 m over about 650 days, or 0.015 m/day). Thus, the calculation agrees well with the measurements for the maximum erosion rates in the area.

Generally for both the measurements and calculations, the depth changes are confined to erosion in the North Channel, and several sites on the shallow shoal areas. The greatest erosion took place in the North Channel in the general vicinity of the SR-105 structure over the measurement period. The calculated erosion was also greatest in this area.

In the calculations, the areas of erosion and deposition tend to be more localized and more extreme than measured. This difference may indicate that there are other mechanisms occurring in nature that smooth the sediment transport and deposition/erosion, which are not being accounted for in the computations. These mechanisms could include diffusion which might spread the effects of transport over a wider area, or direct wave transport (as opposed to wave-generated current transport, which is accounted for in the model), which may smooth out erosion and deposition areas, especially on the shallow shoal areas.

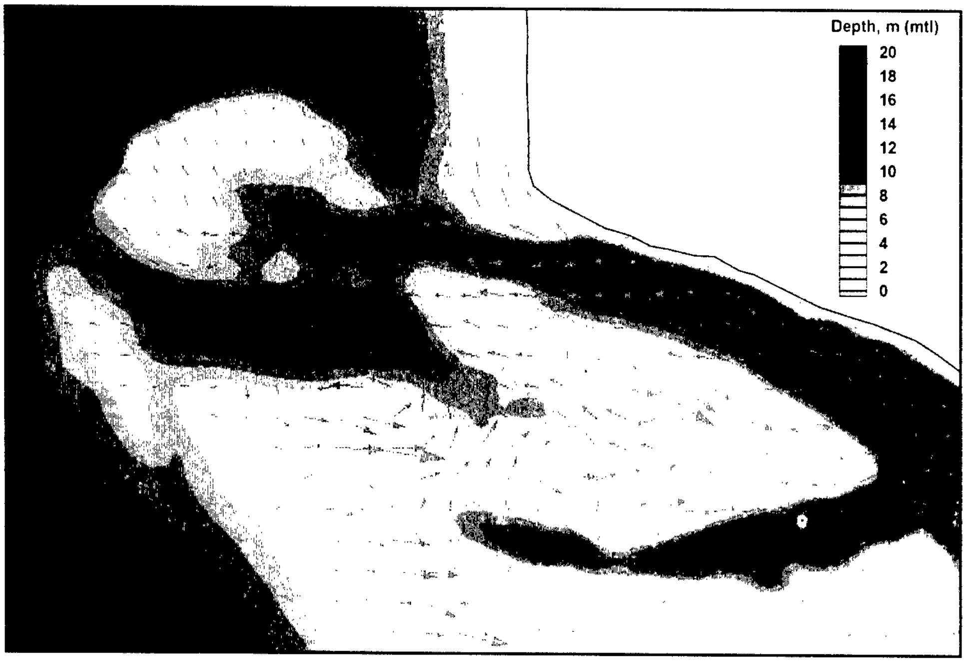


Figure 4-15. Sediment movement vectors, summer 1998

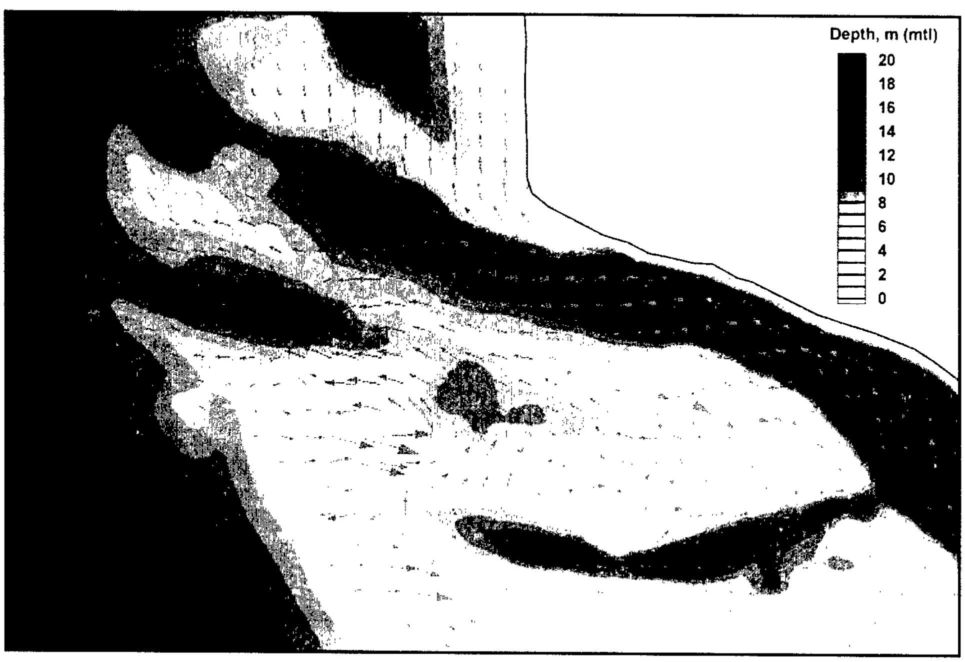


Figure 4-16. Sediment movement vectors, summer 2000

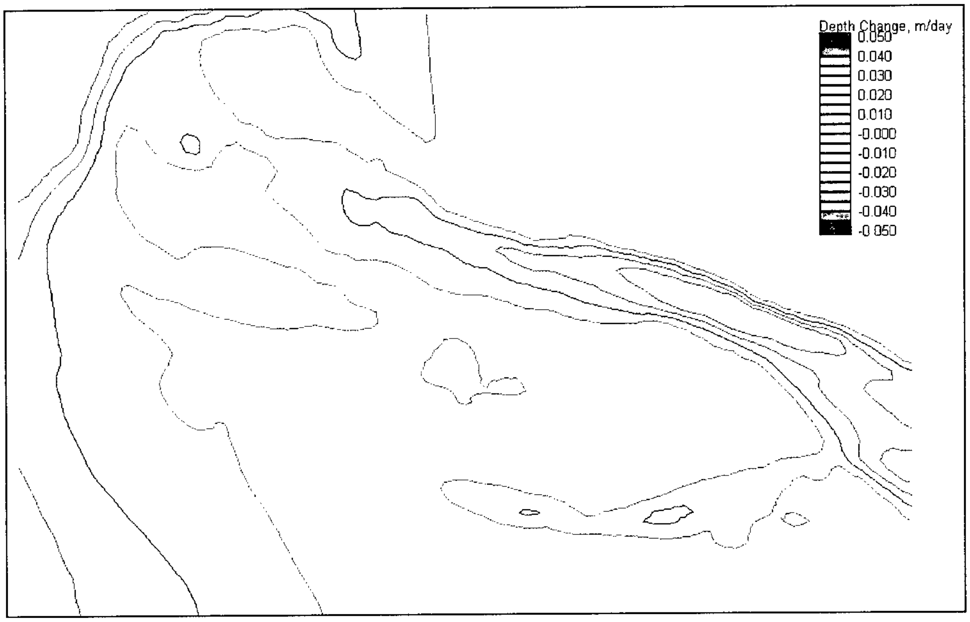


Figure 4-17. Calculated depth change, 2000 bathymetry, tide only

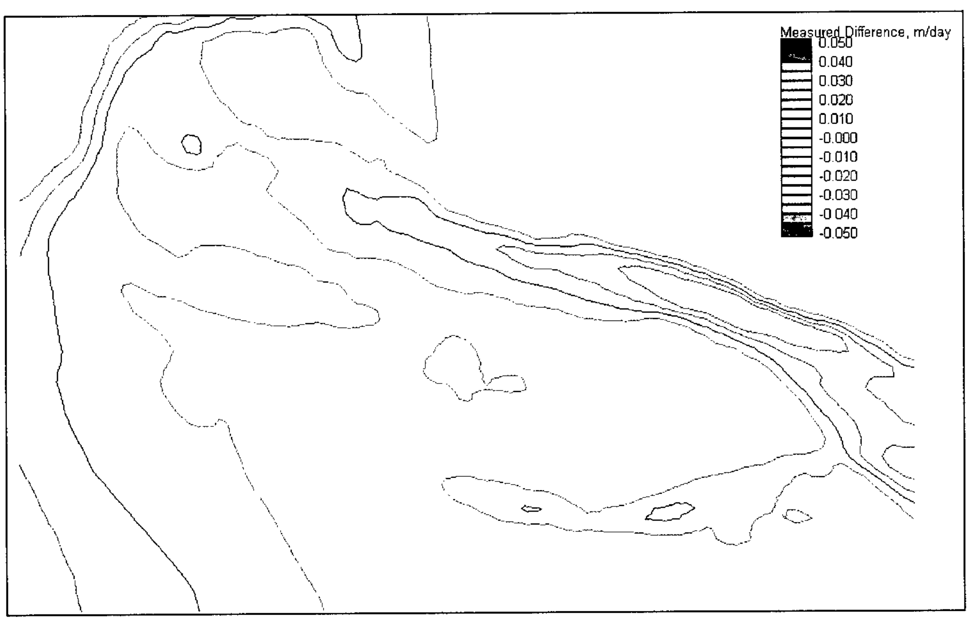


Figure 4-18. Difference in bathymetric measurements, 1998 to 2000

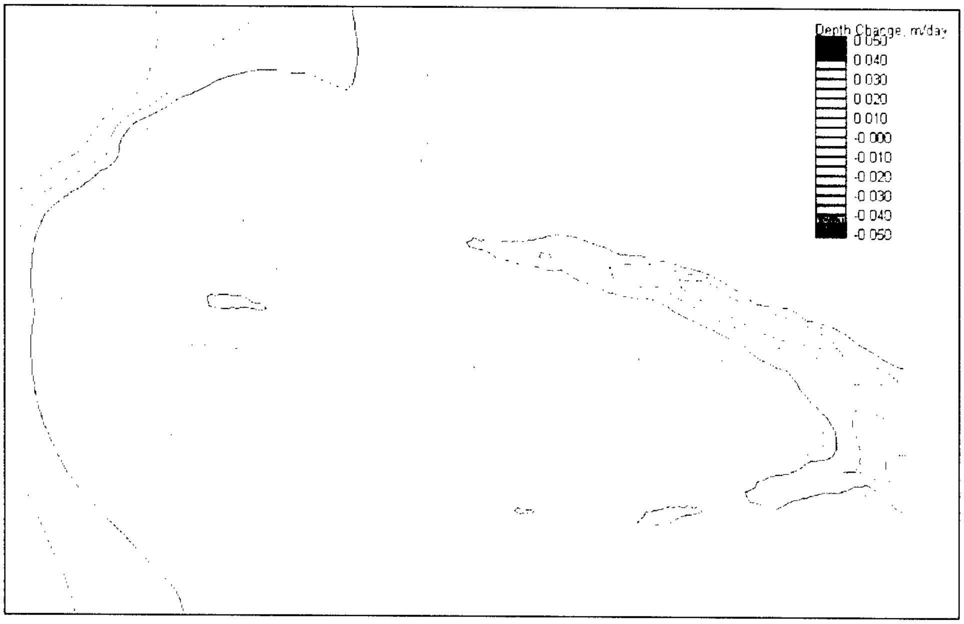


Figure 4-19. Calculated depth change, 1998 bathymetry, tide and fair-weather waves

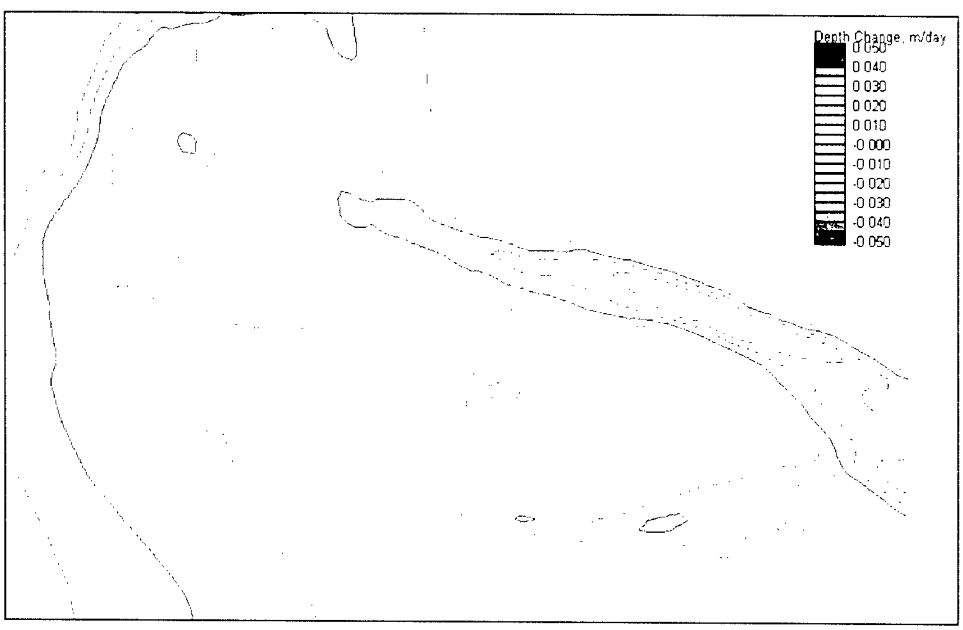


Figure 4-20. Calculated depth change, 2000 bathymetry, tide and fair-weather waves

Areas of calculated erosion and deposition often occur adjacent to one another, especially in the shallow shoal areas. Similar patterns do not occur in the measurements. This calculated pattern may owe to the nature of the forcing, that is, these phenomena are relatively short lived during periods of uniform forcing conditions. More likely, in nature these deposition/erosion patterns do not appear because of the smoothing action discussed previously.

The model does simulate the mild erosion observed along the eastern edge of the shoal. The model does not simulate the deposition area in the center-left portion of the figure. This deposition appears to be related to infilling of a channel from 1998 to 2000. The model may not have simulated this occurrence because it was based on the year 2000 bathymetry where the channel had already been filled. The apparent large area of deposition in the upper left of Figure 4-18 owes to lack of bathymetric data in the 1998 survey, as discussed earlier in this chapter.

Velocities as a response to tide and fair-weather wave forcing were input into the sediment transport model. Figures 4-19 and 4-20 show calculated change in depth for the 1998 and 2000 bathymetries, respectively. In general, the erosion/deposition patterns are similar to the tidal current simulation in Figure 4-17, especially the erosion in the North Channel.

The erosion and deposition across the shoals is greater than with tide acting alone, owing to the greater currents on the shoals generated by the wind and waves. Most of the erosion and deposition over the shoals in the calculations generally occur adjacent to one another, suggesting that these areas are artifacts of the modeling, and are probably smoothed out in nature by other processes.

Similar analyses were conducted with the 1998 and 2000 bathymetries with combined tide and wind- and wave-forced currents for the January 1998 storm. Contour plots of depth change for 2000 and 1998 are shown in Figures 4-21 and 4-22, respectively. For these cases there are large adjacent areas of deposition and erosion across the shoal areas of the inlet. In this case erosion and deposition rates are larger by almost an order of magnitude, or up to 0.1 m/day. The calculation predicts deposition of material within the North Channel in the vicinity of the SR-105 structure. Although the deposition rate is small, approximately 0.05 m/day, it is consistent with expectations that a storm would cause infilling of the navigation channel.

The area of significant erosion in the 2000 bathymetry and significant erosion and adjacent deposition in the 1998 bathymetry just to the south of the North Channel is probably due to a numerical instability in the model in this area, perhaps due to large differences in current velocity extending from the channel to the shallow bar under the storm conditions. The instability is localized, and does not affect other areas of the analysis.

Conclusions for Willapa entrance

The ADCIRC tidal circulation modeling and the sediment pathway analysis demonstrate the controlling processes governing the evolution of the inlet shoals and the North Channel. These tools allow general predictions about the future

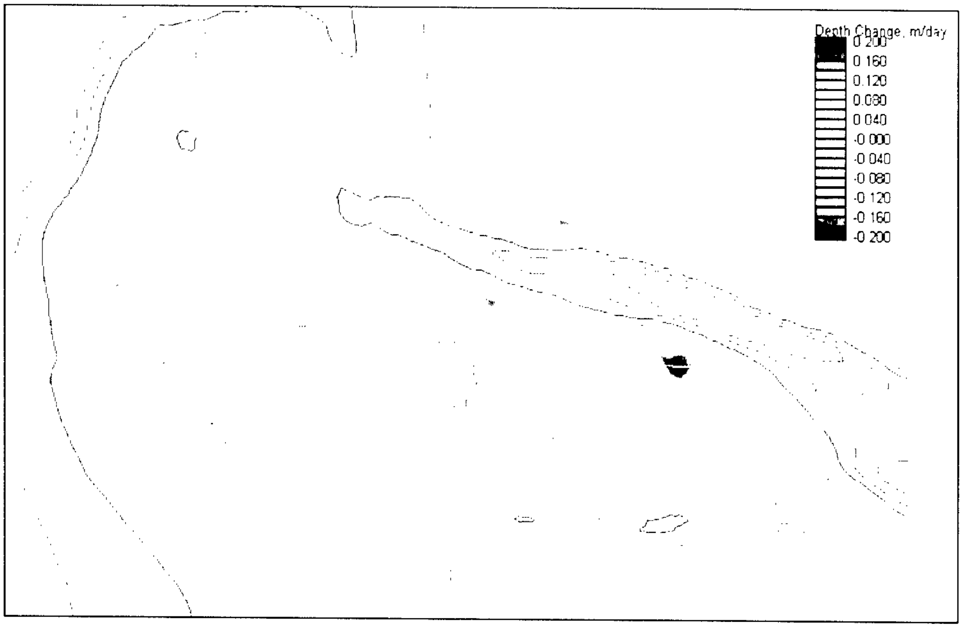


Figure 4-21. Calculated depth change, 2000 bathymetry, tide and January 1998 storm wind and waves

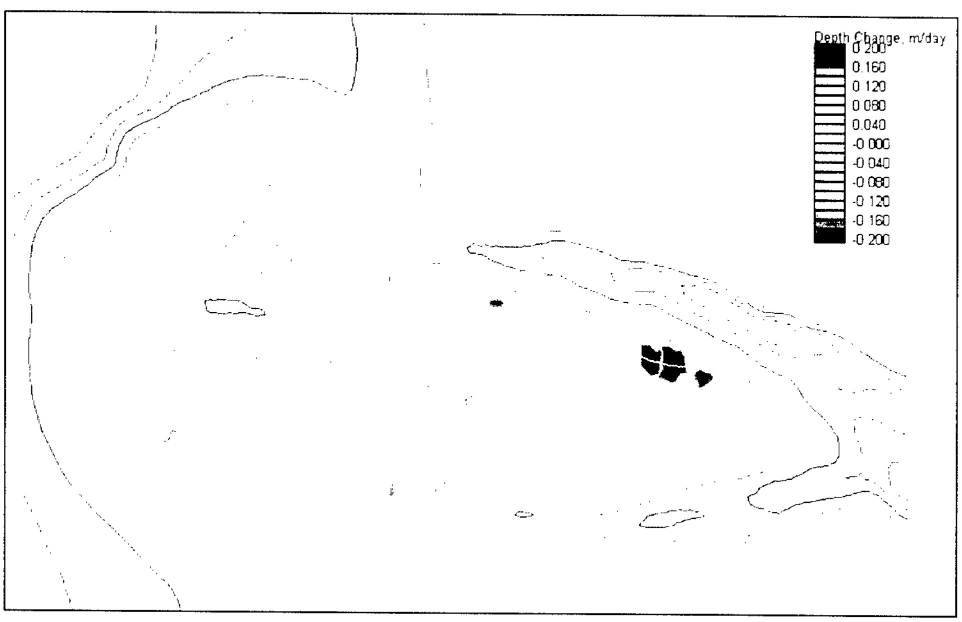


Figure 4-22. Calculated depth change, 1998 bathymetry, tide and January 1998 storm wind and waves

geometry of the channel to be made. Modeling shows that the average movement of shoal sediments is across the shoals on the flood current, and out through the North Channel on the ebb current. This flow pattern leads to growth in the ebb shoal in the vicinity of the seaward end of the North Channel and erosion of the shoals in other areas. Growth of the shoal near the mouth of the North Channel causes the channel to extend seaward at the same time that other potential channel locations become shorter owing to shoal erosion elsewhere. Eventually the outer North Channel becomes hydraulically inefficient, and a new shorter, and more efficient, channel opens up. The old channel gradually fills in and the process of shoal growth repeats at the new channel location.

The alternative channel may just be a branching of the existing channel at the outer end of the shoal, or more infrequently a new channel may break through significantly to the south of the main channel. This would typically occur after the shoal separating the channel from the ocean in this area had eroded so that the more southerly channel is significantly more efficient (shorter) than the typical channel location. The southerly channel would then typically drift north in response to the northward longshore transport. This cycle can take many decades to complete. It is possible to trigger the creation of a new channel location by dredging a new, shorter channel through the shoal to maintain an efficient ebb tide channel for navigation. The type of modeling applied in this analysis can be applied with regular bathymetric measurements to examine the length and hydraulic efficiency of the existing channel relative to other channel configurations. This analysis procedure will give an indication of when it may no longer be feasible to maintain an existing channel.

Bay Center Entrance Channel

In the past, the channel to Bay Center has filled rapidly with sediment after dredging (see Chapter 3). Circulation and sediment transport modeling were conducted to advance understanding of physical processes at the Bay Center Entrance Channel as a control case for further model development at the Willapa Bay entrance. Another goal of the modeling is to provide guidance for channel maintenance at the Bay Center Entrance Channel. A two-phased approach was undertaken for modeling the circulation and sediment transport at Bay Center. In this approach, two circulation numerical models were applied, ADCIRC and M2D (Militello 1998). Simulations over a regional domain were conducted with ADCIRC. M2D was applied over a local domain set entirely within Willapa Bay. The M2D model was selected because it is computationally fast, easy to set up, stable, and has robust flooding and drying algorithms. A sediment transport model was embedded within M2D for calculation of time-varying bottom elevation. This chapter describes the modeling approach and findings of the study.

Regional modeling with ADCIRC

A regional circulation model was established for Willapa Bay during a study of channel reliability through the bay entrance (Militello et al. 2000). This model provided a basis from which the present modeling work was conducted. The original ADCIRC finite-element mesh was specified to resolve proposed channel

configurations in the entrance. For the present study at Bay Center, this level of detail was not required, and some mesh resolution at the entrance was removed to reduce computation time. Figure 4-23 shows the revised mesh for Willapa Bay, and Figure 4-24 displays details of the mesh at the entrance and in the northern bay. Resolution was increased at Bay Center to represent the channel, bars, and shoals. Bathymetry data sets collected in the Willapa entrance during spring 2000 were incorporated into the mesh. At Bay Center, survey data collected in November 2000 replaced the bathymetry in the original mesh. Mesh detail at the Bay Center Entrance Channel is shown in Figure 4-25. The modified ADCIRC mesh contained 22,428 computational nodes.

The role of ADCIRC in the Bay Center study is to provide water-level boundary conditions to a local hydrodynamic model, M2D, which was applied to calculate water level, current, and sediment transport. Measured and ADCIRC-calculated water level and current at and near Bay Center were compared to verify that water levels provided from the ADCIRC simulation are correct boundary conditions. If these water levels were incorrect, comparison between measurements and calculations with M2D would show significant discrepancies.

During development of the ADCIRC mesh in the region of Bay Center, it was found that elevation of the Ellen Sands shoal, just north of the Bay Center Entrance Channel, exerts strong control on the flow through the channel. Initial representation in the model specified the shoal too low, which did not constrain flow sufficiently through the channel. Increasing the elevation of the shoal improved comparison with measurements. Further estimation of the shoal elevation was conducted within the M2D modeling (described in the following section), and the shoal bathymetry determined from the M2D calculations was applied to the ADCIRC mesh and the M2D grid. Similarly, elevations of the tidal flat area to the south of the entrance channel were adjusted to be more realistic. Bathymetric data for these shallow areas are not presently available so elevations of the flats were estimated from aerial photographs and the tidal elevation.

Local modeling with M2D

The two-dimensional finite-difference model M2D was applied in the vicinity of Bay Center to calculate water level, current, sediment transport, and morphology change. M2D solves the horizontal equations of mass and momentum conservation on a rectilinear grid. Cell sizes vary over the computational domain. Features of the model are: inclusion of the nonlinear continuity and advective terms, robust wetting and drying algorithms, fast computation time, and a newly-implemented sediment-transport algorithm that calculates change in depth over time. Bottom friction in the hydrodynamic model is specified through the Manning roughness coefficient.

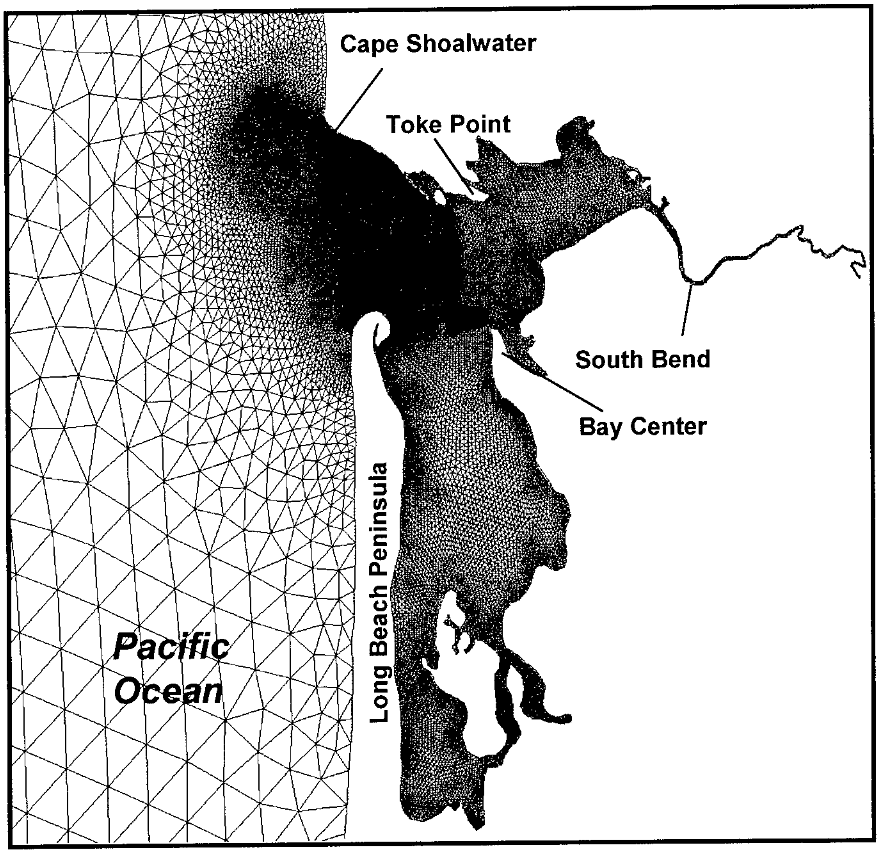


Figure 4-23. Mesh of Willapa Bay modified for detailed calculations at Bay Center

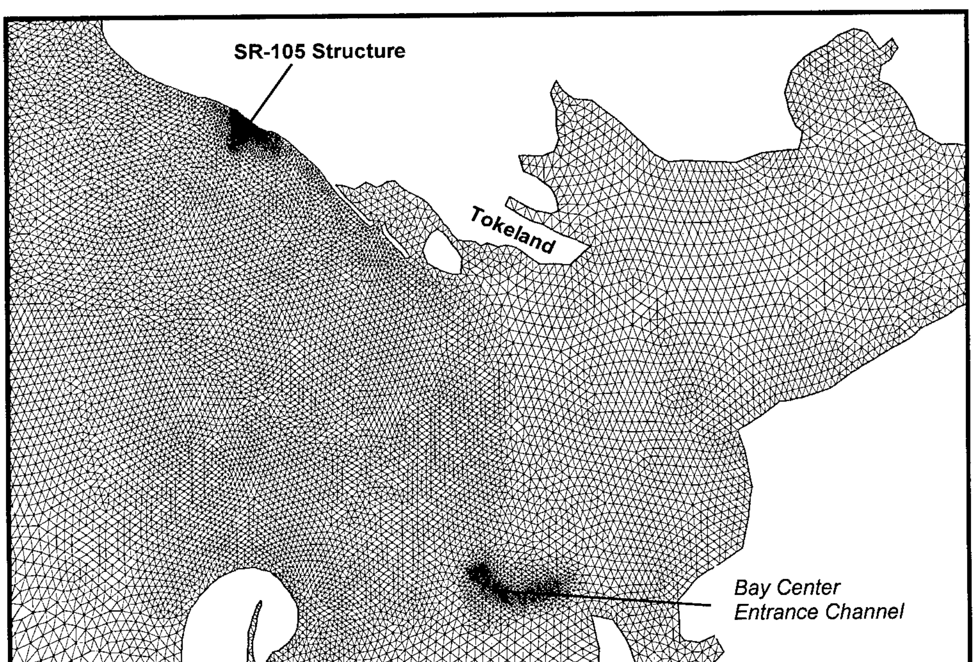


Figure 4-24. ADCIRC mesh at entrance and upper Willapa Bay

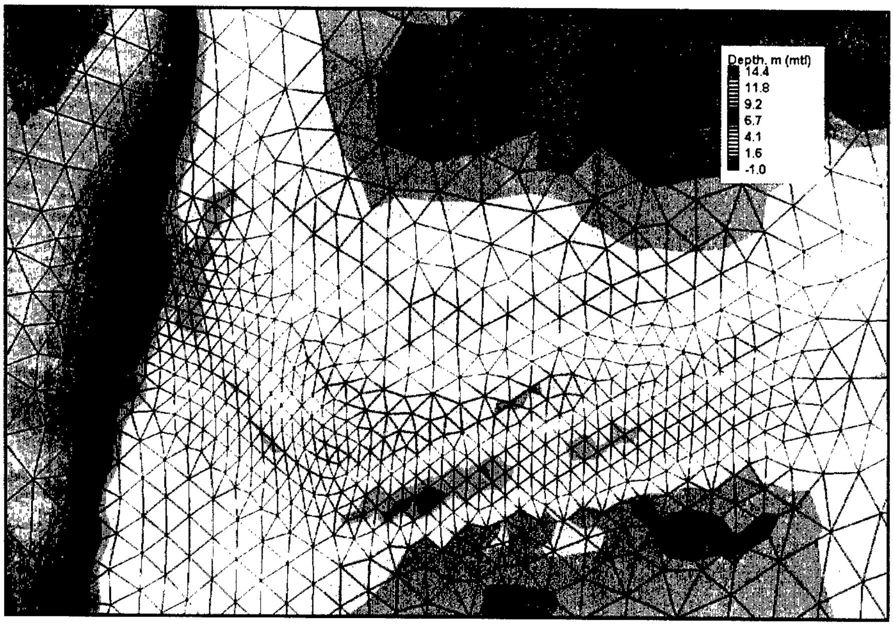


Figure 4-25. Detail of ADCIRC mesh at Bay Center Entrance Channel

The local M2D grid was developed from the identical bathymetry as the ADCIRC mesh. The domain of the grid covers the upper and middle portions of Willapa Bay, with the Bay Center Entrance Channel located approximately in the center of the grid (Figure 4-26). Detail of the grid at the entrance channel is shown in Figure 4-27. Cell side dimensions range from 170 to 37 m. In the dredged portion of the Bay Center Entrance Channel where the grid is most resolved, cell dimensions are approximately 40 × 40 m. This resolution at the entrance channel is comparable to that in the ADCIRC mesh. Values of the Manning roughness coefficient were specified from 0.028 to 0.033 sec/m$^{1/3}$. Greater values of the friction coefficient were specified in shallow water, such as at tidal flats. The M2D grid contains 7,421 cells, and simulations were conducted with a 0.25-sec time-step.

Forcing for the M2D model consisted of water-level time series calculated by ADCIRC and applied at the M2D boundaries. Locations of these boundaries were the entrance, Willapa River, and southern bay. For the Willapa River and southern bay boundaries, one time series of water level taken from the center of the corresponding channel in the ADCIRC simulation was applied across the boundary. Because tidal phase varies across the entrance to Willapa Bay, each M2D cell along the entrance boundary was forced with a time series of water level that corresponded to the ADCIRC node closest to the cell center. This specification describes water-level forcing across the entrance that includes the tidal phase distribution. Figure 4-28 displays an example of an ADCIRC node from which water-level values were calculated to provide boundary forcing for an M2D cell.

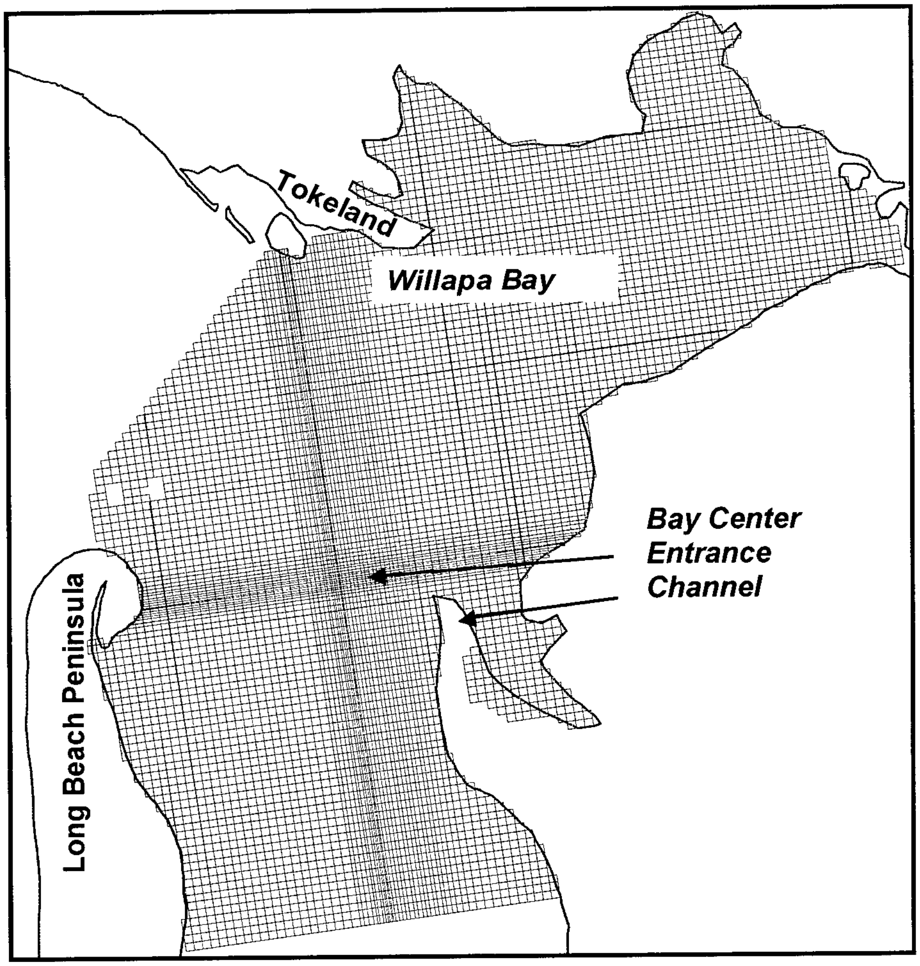


Figure 4-26. M2D grid of upper Willapa Bay

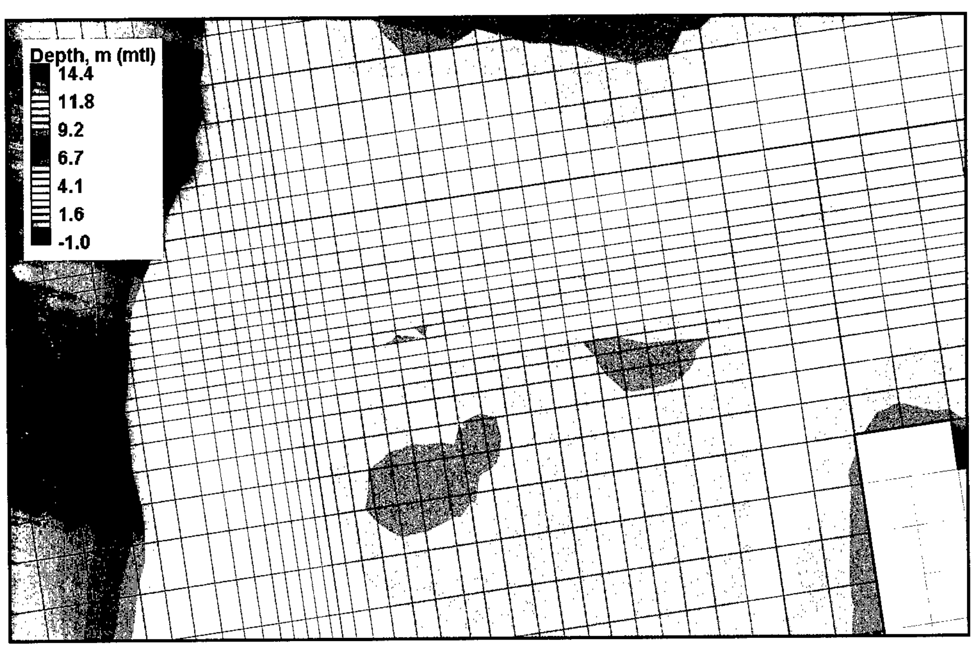


Figure 4-27. Detail of M2D grid at Bay Center Entrance Channel

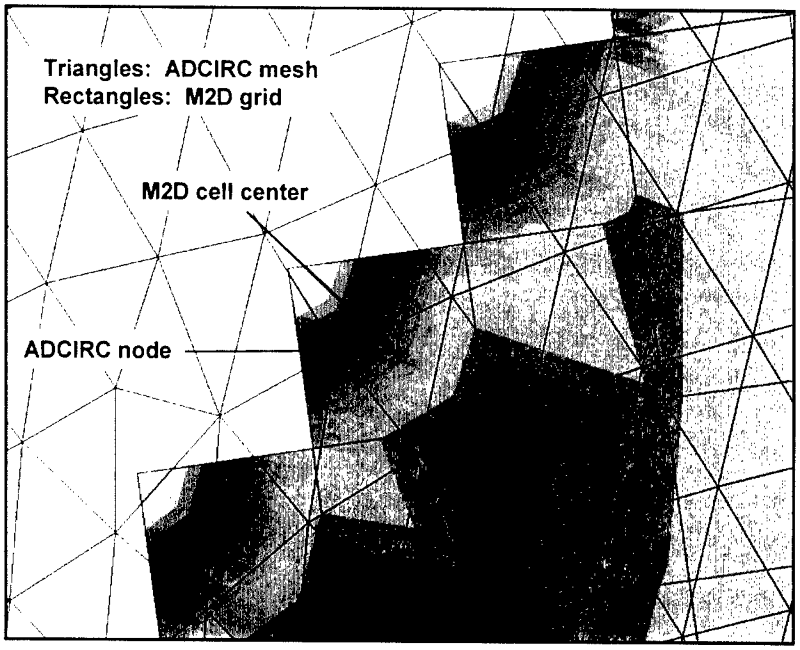


Figure 4-28. ADCIRC node prescribed to give M2D boundary condition

Performance of the ADCIRC model was demonstrated in the simulations described in the modeling chapter of the Willapa entrance channel feasibility report (Militello et al. 2000). Similarly, performance of the M2D model is described here through comparison with ADCIRC calculations and with measurements. Simulations were conducted for a 5.5-day interval to compare water level and velocity values calculated by M2D and ADCIRC. The ADCIRC simulation started on 12 November 2000, and 1 day was given for the model to ramp to full forcing. All reported times for simulations are in Greenwich Mean Time (GMT). Water level and velocity values were output from ADCIRC starting at 1 day of elapsed simulation time. Water levels were taken from the ADCIRC solution and applied as boundary forcing for the M2D simulation. M2D was then ramped to full forcing by the boundary conditions over a 1-day interval. Thus, solutions between ADCIRC and M2D can be compared for the simulation time after both model ramps have completed. This interval started 2 days after the beginning of the ADCIRC simulation and 1 day after the beginning of the M2D simulation.

Water level and velocity between ADCIRC and M2D were compared for the numerical stations distributed over the M2D computational domain (Figure 4-29). Five stations were selected to represent deep channels, tidal flats, and locations of measurement sites at Bay Center. Comparisons of water level and current speed for the two models at stas 1 and 2 are discussed. Stations 1 and 2 were selected as representative of a station on a tidal flat and one in a main

Figure 4-29. Numerical station locations

channel, respectively, both in the vicinity of the Bay Center Entrance Channel. Because calculation points for the two models are not at identical locations, comparisons are shown for the closest ADCIRC node and M2D cell.

Comparisons of water level and velocity for sta 1 from 14 November through 17 November 2000 are shown in Figures 4-30 through 4-32. This is a typical interval and representative result. Water depth at sta 1 is 0.2 m in the mesh and grid. This station becomes inundated and dried through the tidal cycle, as seen in Figure 4-30 by the absence of the lower-tide portion of the curve. Water level calculated by ADCIRC and M2D was nearly identical. In addition, the wetting and drying algorithms of both models are stable and robust. Times of drying and wetting are consistent between the two models.

North-south and east-west components of velocity at sta 1 are compared between ADCIRC and M2D in Figures 4-31 and 4-32, respectively. For both components, the velocity patterns are similar. Peak velocities calculated by M2D are consistently weaker than those calculated by ADCIRC by approximately 0.05 to 0.1 m/sec. The north-directed velocity (flood) calculated by M2D leads that calculated by ADCIRC. The south-directed velocities (ebb) calculated by the two models are in phase. The models apply different forms of friction, which accounts for part of the discrepancy in speed at this shallow numerical station. Also, velocities associated with flooded and dried cells may differ between the two models.

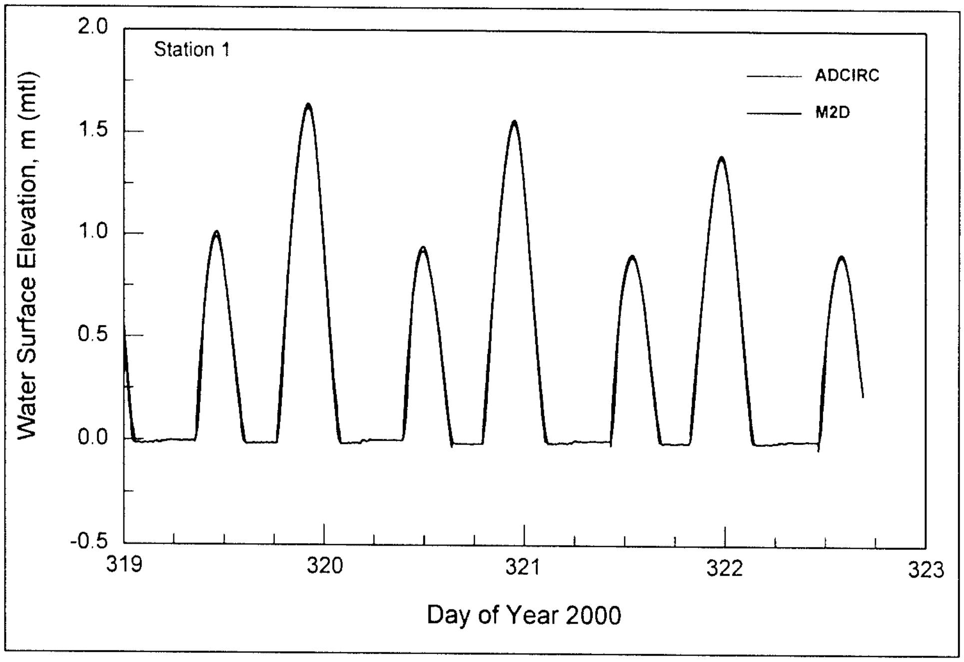


Figure 4-30. Comparison of calculated water level between ADCIRC and M2D at sta 1

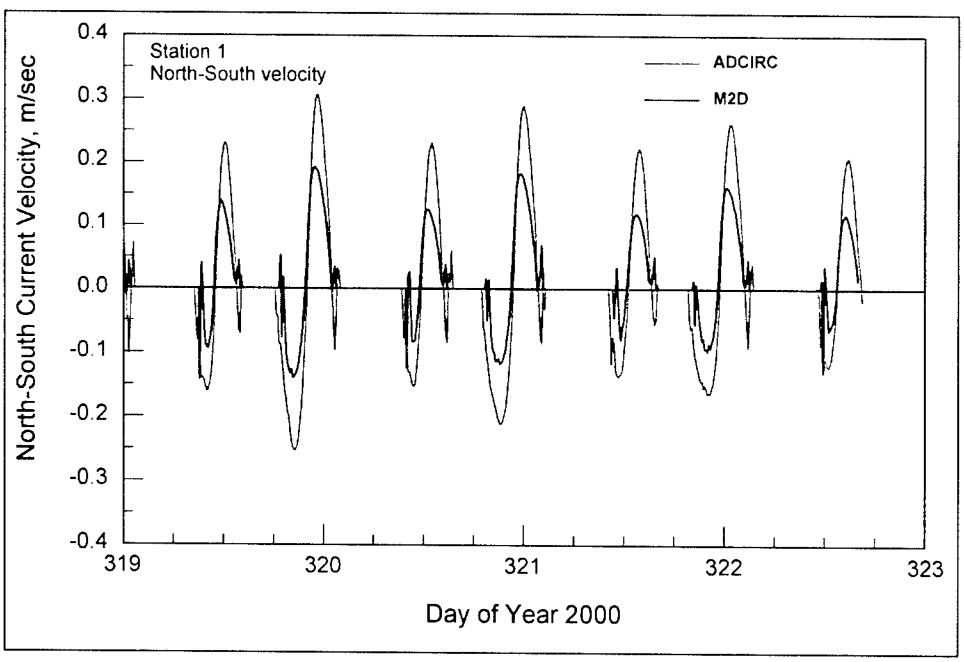


Figure 4-31. Comparison of calculated north-south component of velocity between ADCIRC and M2D for sta 1

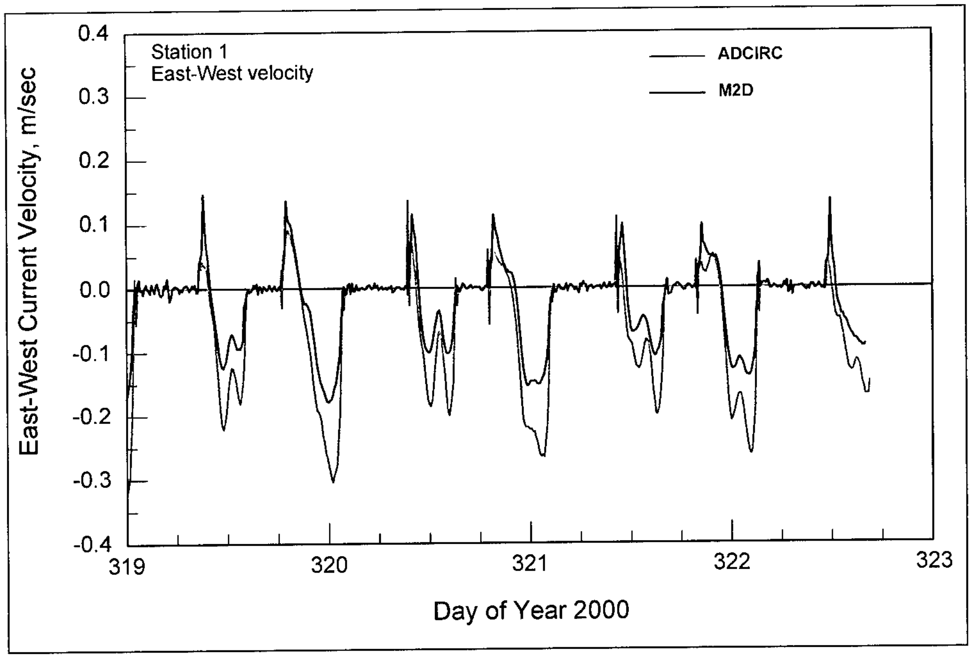


Figure 4-32. Comparison of calculated east-west component of velocity between ADCIRC and M2D for sta 1

Comparisons of water level and velocity for sta 2 from 14 November through 17 November 2000 are shown in Figures 4-33 through 4-35. Depth at sta 2 is 13.9 m. Water level calculated by the two models is nearly identical (Figure 4-33). The north-south component of velocity computed by M2D is slightly weaker than that calculated by ADCIRC by approximately 0.02 m/sec during peak north-directed flow, and slightly stronger by approximately 0.08 m/sec during south-directed flow. The east-west component of velocity computed by M2D is weaker than that calculated by ADCIRC by approximately 0.2 m/sec for both east- and west-directed flow. Phases of the current are the same. The differences in velocity between the two models may owe to variation in grid and mesh resolution, and treatment of the advective terms.

Elevations of the tidal flats in Willapa Bay are ambiguous. For modeling of the Bay Center Entrance Channel, the bathymetry of the Ellen Sands area and tidal flats directly south of the channel (South tidal flat) exert control on the entrance channel velocity. Sensitivity testing of the ADCIRC model revealed that the elevations of the Ellen Sands and South tidal flat of the entrance channel were too low in the original mesh. Raising the elevation of these tidal flats in the mesh and comparing the calculated current to measurements gave improvements at the middle measurement station.

Further adjustment of the tidal flat bathymetry at Ellen Sands and South tidal flat was conducted through visual means. A composite aerial photograph was overlaid on the M2D grid and approximations of the elevations were made. The aerial photographs were taken on 6 November approximately 45 min before low tide at 0.9 m (3.1 ft) mllw. Figure 4-36 shows the composite aerial photograph and the estimated bathymetry. The depth of Cutoff Channel, located east of Ellen Sands, is unknown. Bathymetry for this channel was also estimated from the aerial photograph composite.

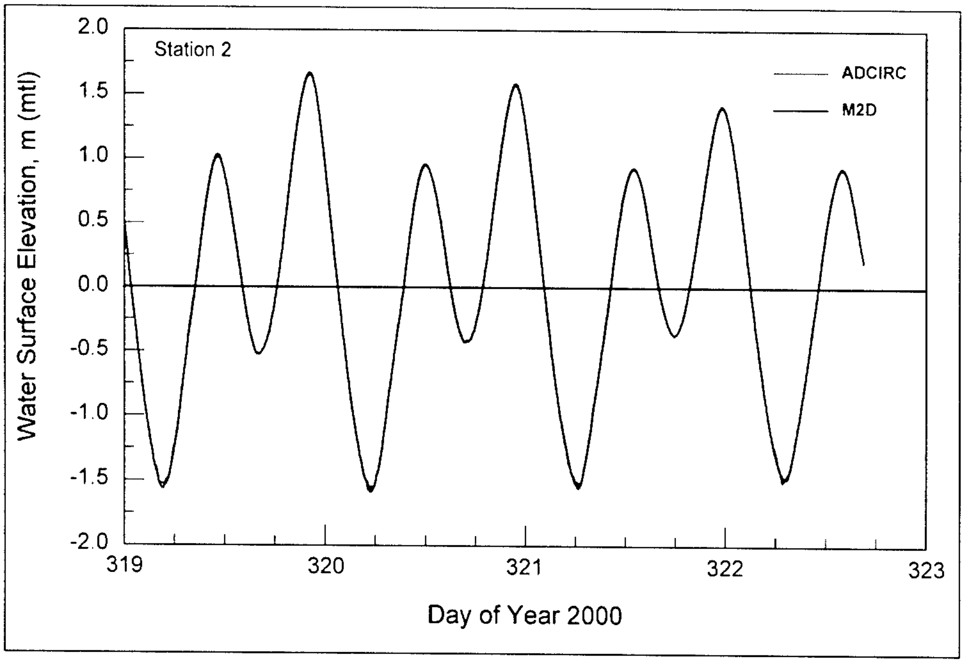


Figure 4-33. Comparison of calculated water level between ADCIRC and M2D at sta 2

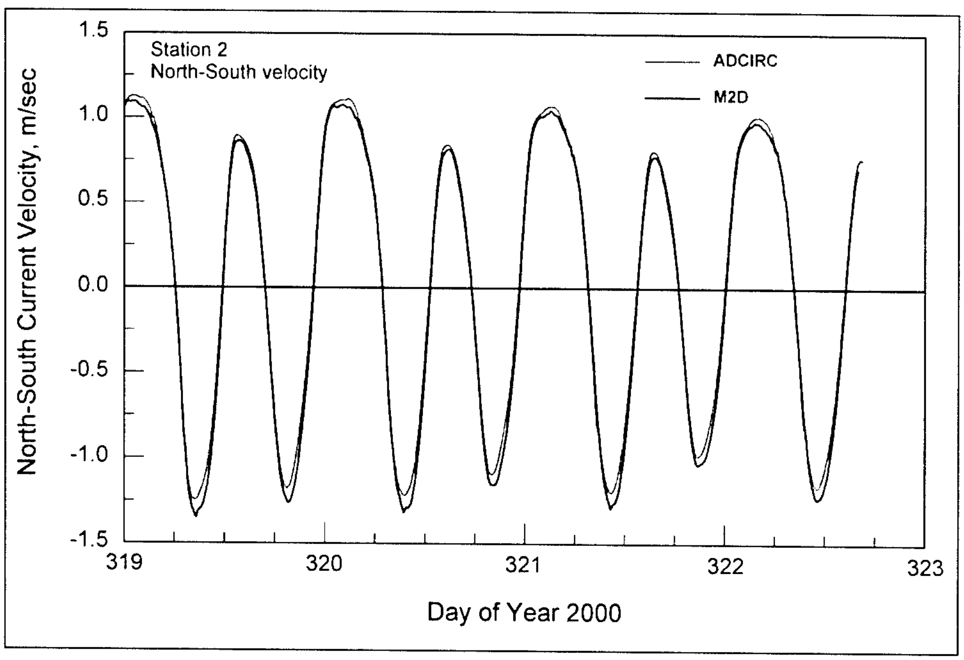


Figure 4-34. Comparison of calculated north-south component of velocity between ADCIRC and M2D for sta 2

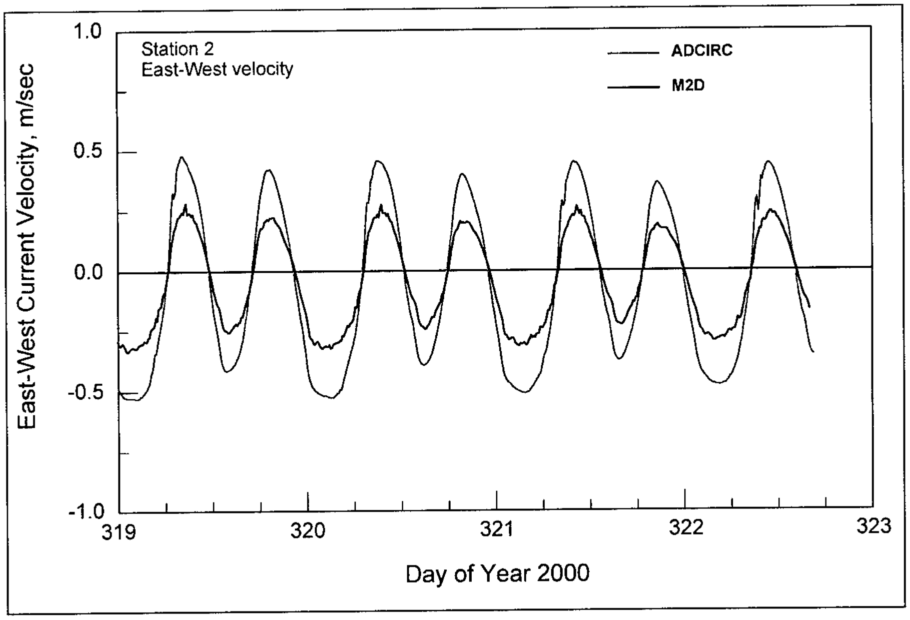


Figure 4-35. Comparison of calculated east-west component of velocity between ADCIRC and M2D for sta 2

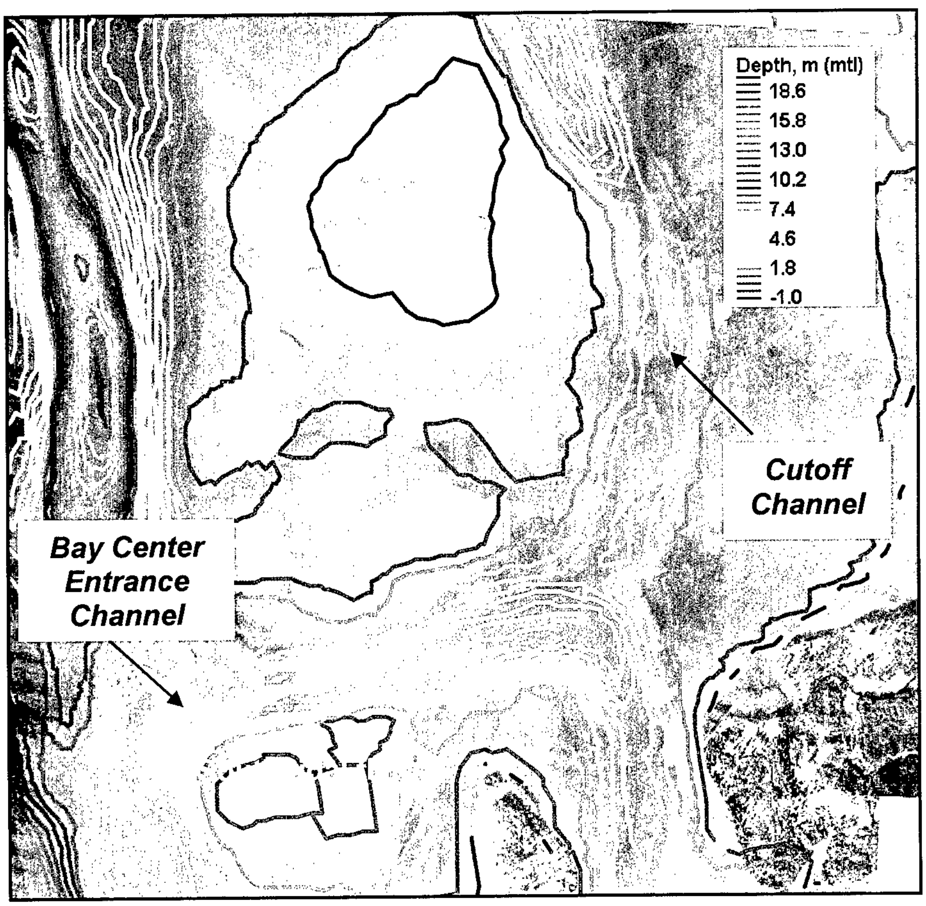


Figure 4-36. Estimated bathymetry of Ellen Sands, South tidal flat, and Cutoff Channel

Verification of the M2D model at Bay Center was conducted by comparison of velocity and water level with field measurements taken at the west, middle, and east stations. Numerical stations that correspond to the west, middle, and east measurement stations are stas 3, 4, and 5, respectively (Figure 4-29). Time series of north-south and east-west components of the current are compared, followed by time series of water level.

Comparison of measured and calculated north-south and east-west components of velocity at the west measurement station for the time interval 14-24 November 2000 (days of year 319 to 330), are shown in Figures 4-37 and 4-38, respectively. There is agreement between the measurements and the velocity calculated by M2D. The calculated north-south component of velocity tracks the measured velocity well. There is an overprediction ranging from near 0 to about 0.25 m/sec during the greater peak southerly flows. Peak northerly flows match well, with the velocity calculated by M2D lying almost on top of the measurement. The calculated east-west component of the velocity is in phase of the measured current, but underpredicts the peak west current by 0.1 to 0.3 m/sec. Peak easterly velocities match well. The maximum error for both components occurs during peak flood velocity, with the model overpredicting the current toward the south and underpredicting toward the west. This situation indicates that the current direction calculated during peak flood is directed slightly more toward the south than the measured current. Direction during peak ebb is well represented by the model, as the north and east-directed currents closely follow the measurements. The measured and calculated currents are in phase for both components of the current.

The middle measurement station lies within the Bay Center Entrance Channel. At this location, the flow is primarily along the channel, which is approximately oriented along an ENE-WSW axis. Comparison of measured and calculated north-south and east-west components of the current are given in Figures 4-39 and 4-40, respectively. The calculated north-south current follows the general trend of the measured current, but the calculated velocity typically underpredicts the measured. In addition, the calculated current shows greater high-frequency variation. The calculated east-west component of the current tracks the measured current well. Peak east and peak west velocities are reproduced. Tidal phase of the east-west component matches well for east-directed flow (flood), and calculations lag measurements for stronger west-directed flow (ebb). This lag may owe to inaccuracies in bathymetry of the tidal flats such that flow off of them is delayed in the model. Weaker ebb-directed flows are in phase with the measured tidal current. Thus, the primary flow component along the entrance channel is reasonably calculated by M2D.

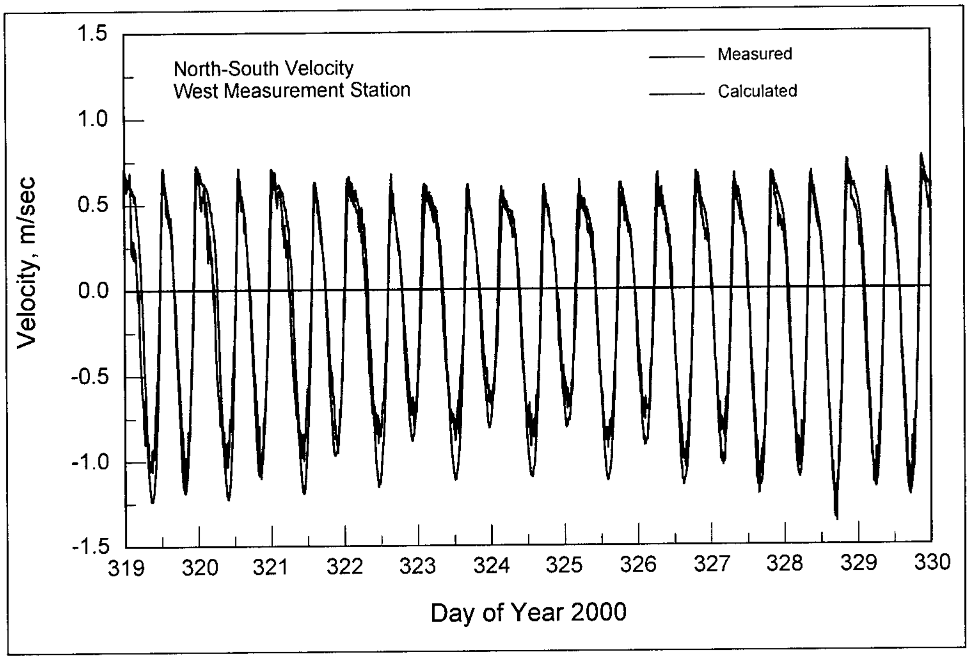


Figure 4-37. Measured and M2D-calculated north-south velocity at west measurement station, 14-24 November 2000

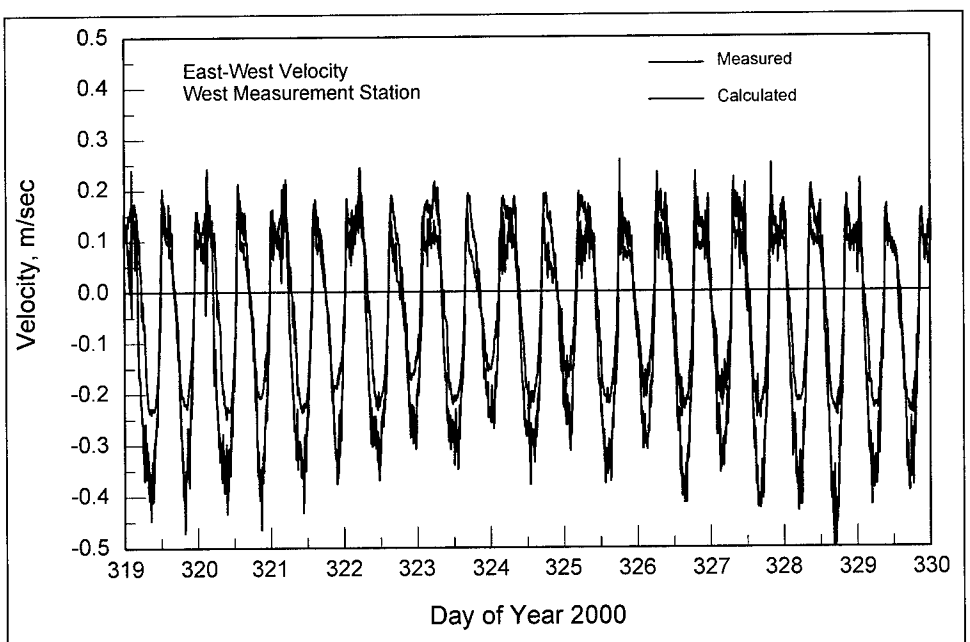


Figure 4-38. Measured and M2D-calculated east-west velocity at west measurement station, 14-24 November 2000

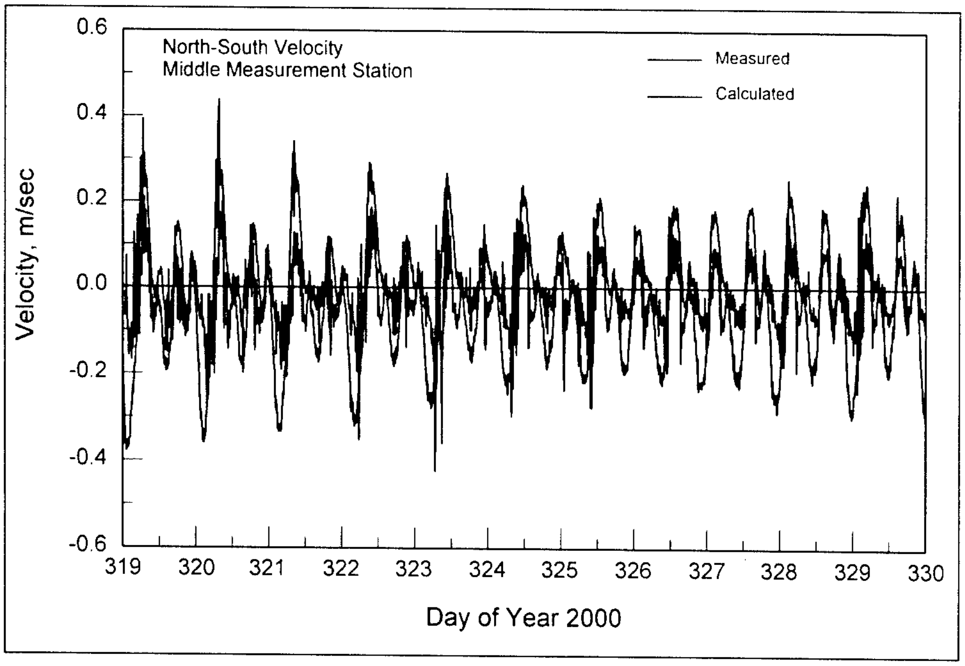


Figure 4-39. Measured and M2D-calculated north-south velocity at middle measurement station, 14 - 24 November 2000

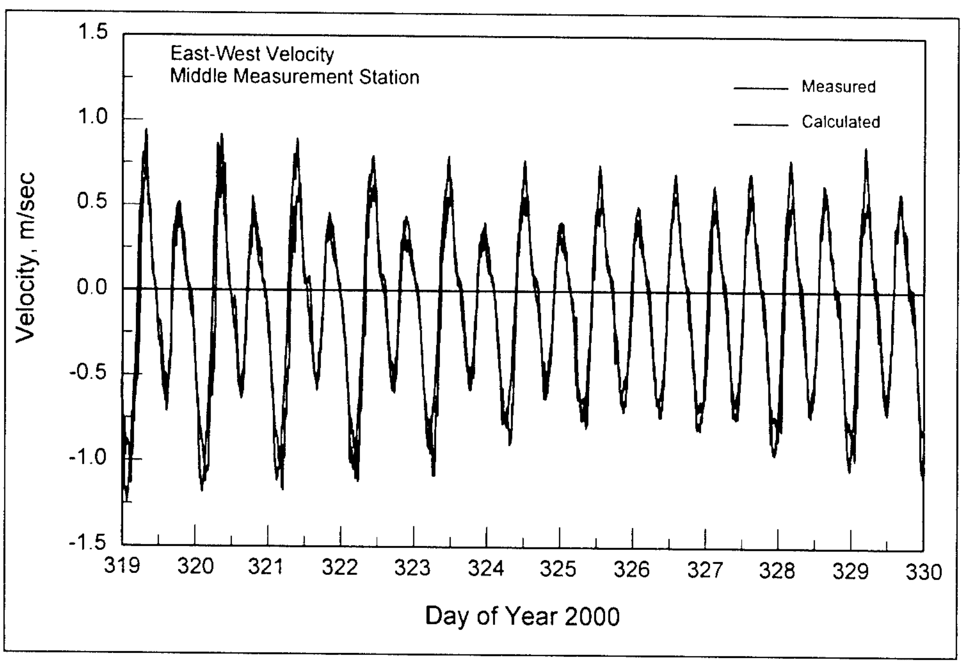


Figure 4-40. Measured and M2D-calculated east-west velocity at middle measurement station, 14 - 24 November 2000

Comparisons of measured and calculated north-south and east-west velocities at the east measurement station are shown in Figures 4-41 and 4-42, respectively. The east-west component of velocity is significantly stronger than the north-south component. The calculated north-south component of velocity is typically weaker than that measured. The pattern of the calculated north-south component of velocity follows the ebb and flood cycles, but does not reproduce them well. Comparison of the east-west component of the current shows better agreement than the north-south component. The model reproduces the overall pattern of ebb and flood flow, and the peak east-directed velocities are underestimated by approximately 0.1 m/sec. Calculated west-directed velocities are significantly underpredicted by approximately 0.5 m/sec during peak flow. A significant portion of the error in the calculated current at this location owes to the absence of bathymetric data for Cutoff Channel. Measurements indicate a strong west-directed flow that is not reproduced by the model. This situation indicates that calculated flow along Cutoff Channel is restricted, possibly by water that is too shallow or drying of cells that should remain wet. Acquisition of bathymetric survey data along Cutoff Channel would improve the predictive capability at this location.

Comparisons of measured and M2D-calculated water levels for the west, middle, and east stations are shown in Figures 4-43, 4-44, and 4-45, respectively. The agreement between measured and calculated water level is similar for the three stations. Tidal variation in water level is well represented by the model. During times of greater tide range, such as from day of year 319 through 324, the low tide is underpredicted by the model, meaning that the calculated water level is not as low as the measured water level. If the tide range is smaller, such as from day of year 326 to 329, the calculated water level closely matches the measurements. The increased difference present during times of greater tide range probably owes to error in tidal amplitude specification of one or more constituents applied at the ocean boundary of the ADCIRC model.

The overall good agreement between the calculated and measured currents indicates that wave-induced currents have only a minor contribution to the total current in the vicinity of Bay Center. Thus, the currents at Bay Center are primarily driven by the tide.

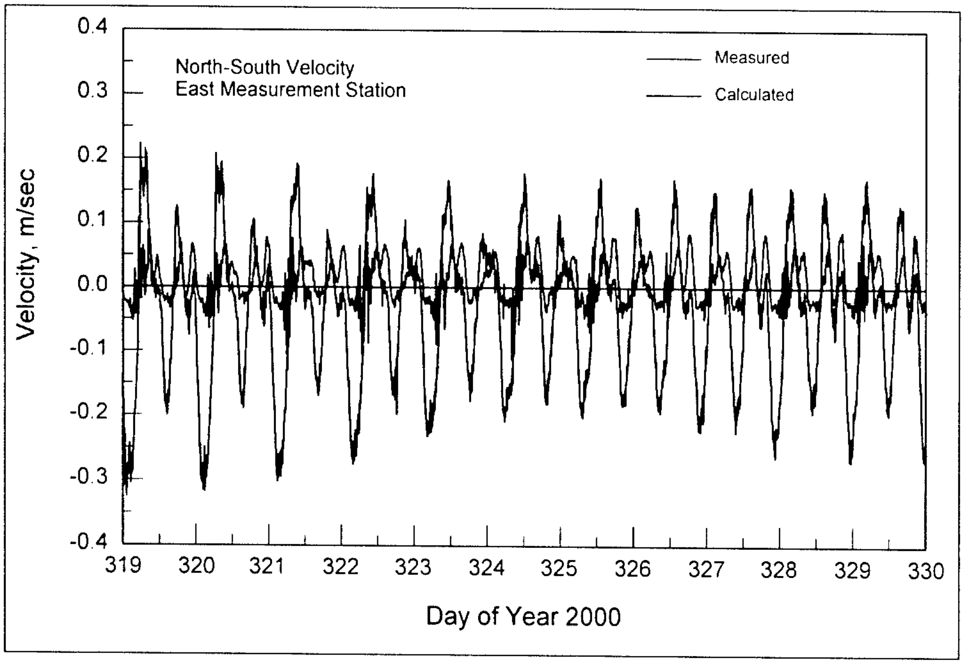


Figure 4-41. Measured and M2D-calculated north-south velocity at east measurement station, 14-24 November 2000

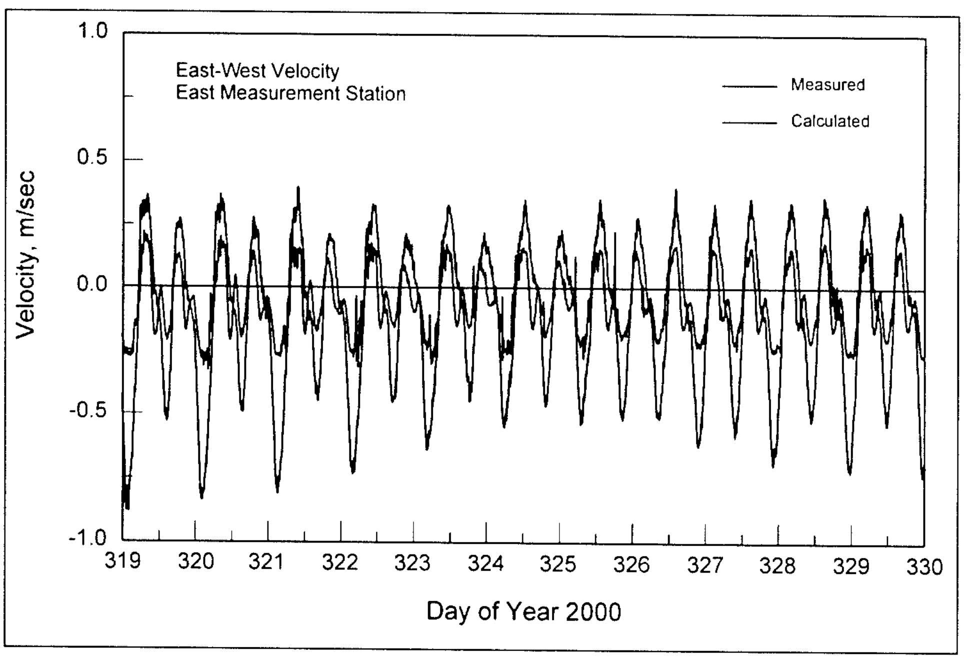


Figure 4-42. Measured and M2D-calculated east-west velocity at east measurement station, 14-24 November 2000

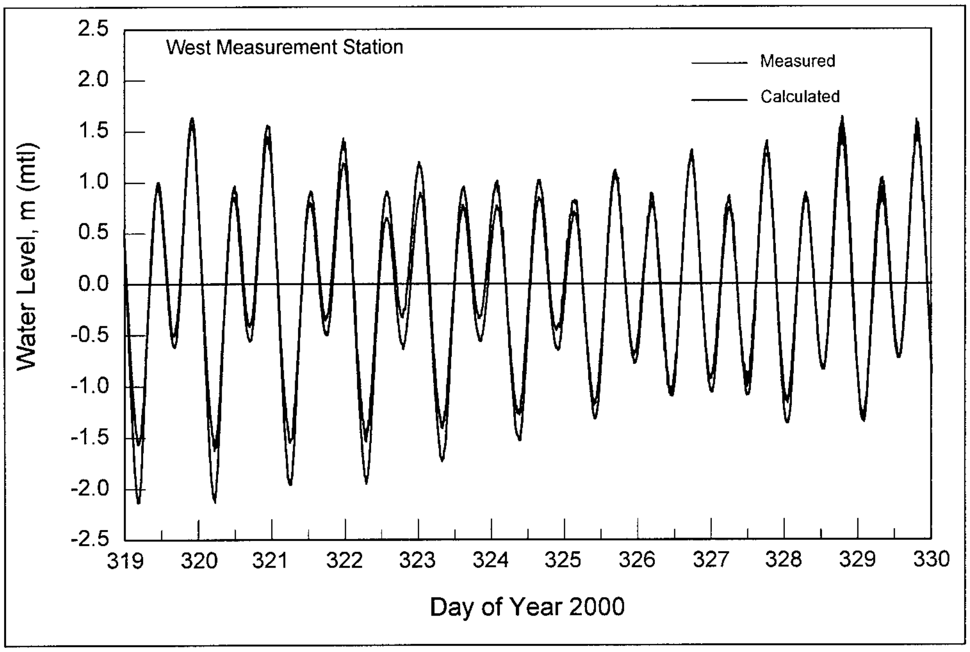


Figure 4-43. Measured and M2D-calculated water level at west measurement station, 14-24 November 2000

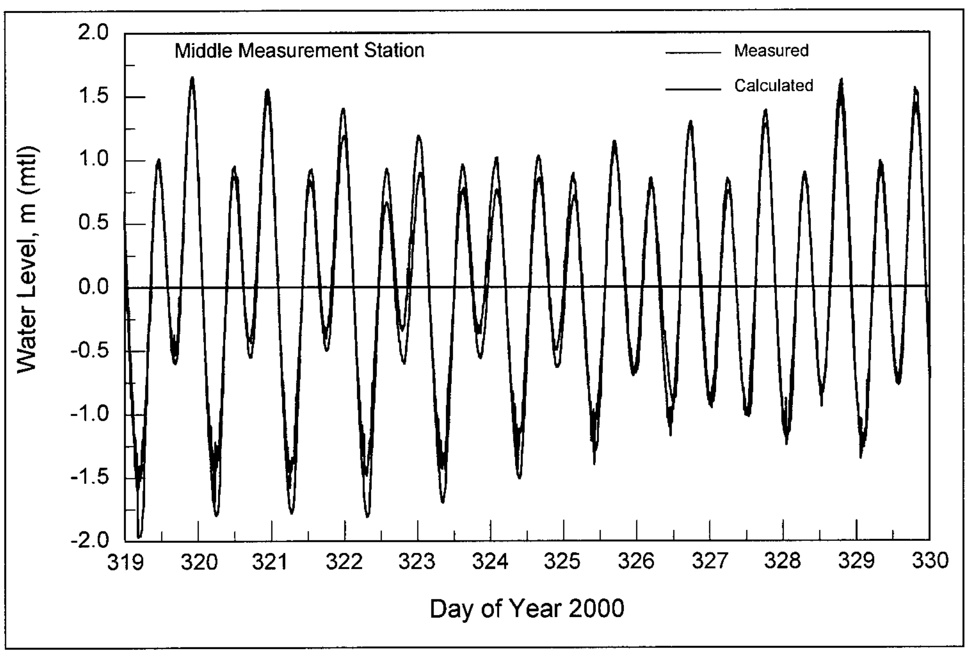


Figure 4-44. Measured and M2D-calculated water level and middle measurement station, 14-24 November 2000

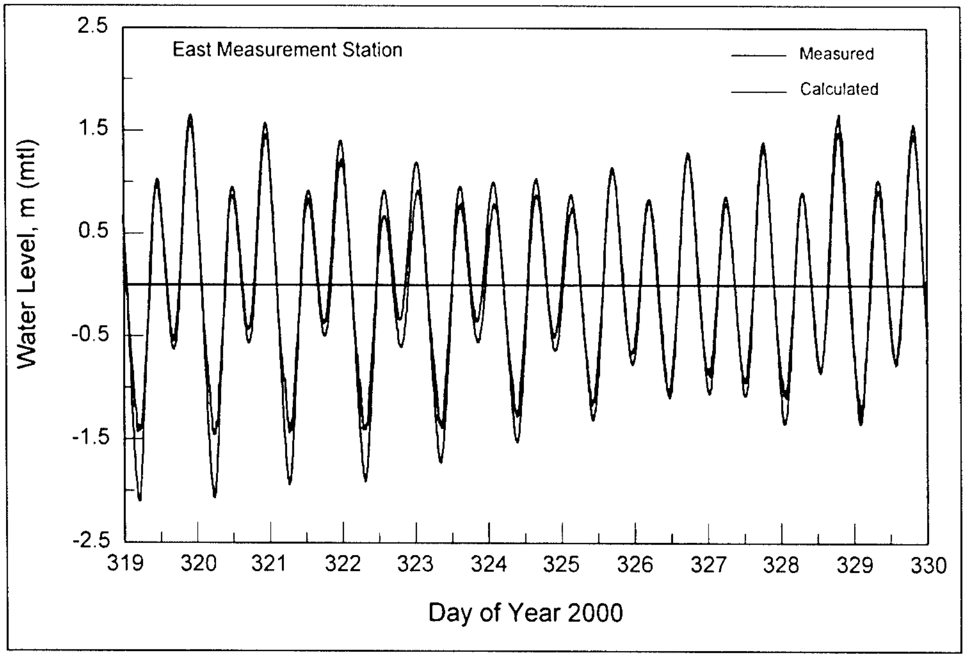


Figure 4-45. Measured and M2D-calculated water level at east measurement station, 14-24 November 2000

Figures 4-46 through 4-49 show horizontal current patterns in Willapa Bay at 4-hr intervals for a total of 12 hr starting at 0400 on 17 November 2000. Vectors denote relative strength of the current and contours show depth. This interval was selected as representative of one cycle of the semidiurnal tidal current in Willapa Bay. Vectors are plotted at regular intervals, not at each cell. The lengths of the vectors denote relative strength, with longer vectors representing stronger currents. Contours denote depth. Figure 4-46 shows ebb current at 0400 (day of year 322.17). Stronger currents are present in the deeper channels and weaker currents on the tidal flats. Ebb flow is present throughout the bay. Water is flowing off of the Ellen Sands shoal in response to the lowering water level in the deeper channels and at the perimeter of the shoal.

Figure 4-47 shows the velocity vectors at 0800 (day of year 322.33), a time when the tidal current is turning from ebb to flood. Weak velocities are present over the bay. In the Willapa River, the current is beginning to flood. Along most of the Nahcotta Channel, except along the east margin (near the Bay Center Entrance Channel) the water is still ebbing. This distribution of ebb and flood currents demonstrates that the model calculates the spatial variation in tidal phase over the bay. In addition, a larger area of the Ellen Sands shoal is dry, as compared to that in Figure 4-46.

Velocity vectors at 1200 (day of year 322.50), are shown in Figure 4-48. At this time, the tide is flooding over the entire bay. South-directed flow along the Nahcotta Channel is strong and there is flow onto and over all of the tidal flats. Water is flooding the Ellen Sands shoal from all directions.

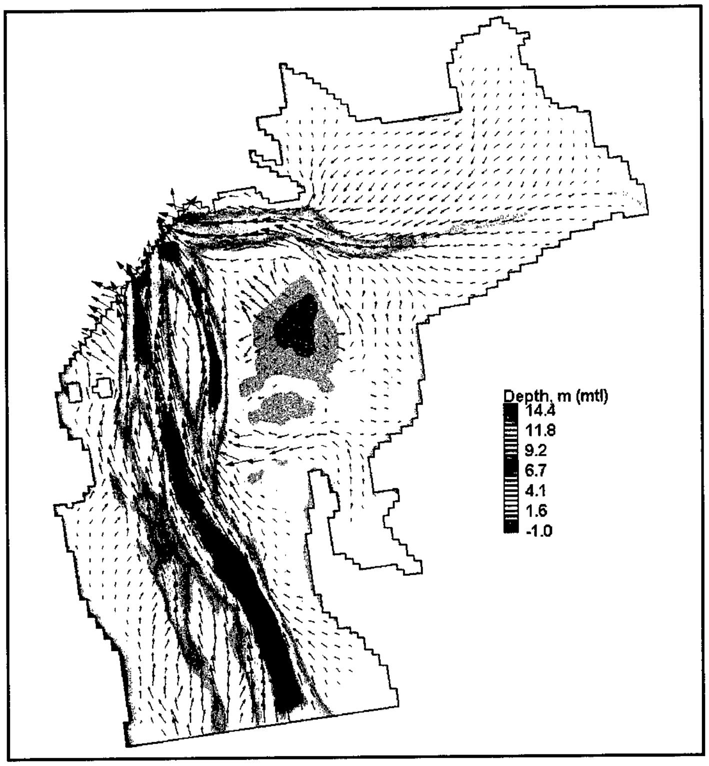


Figure 4-46. Velocity vectors on 17 November 2000 at 0400 (day of year 322.17)

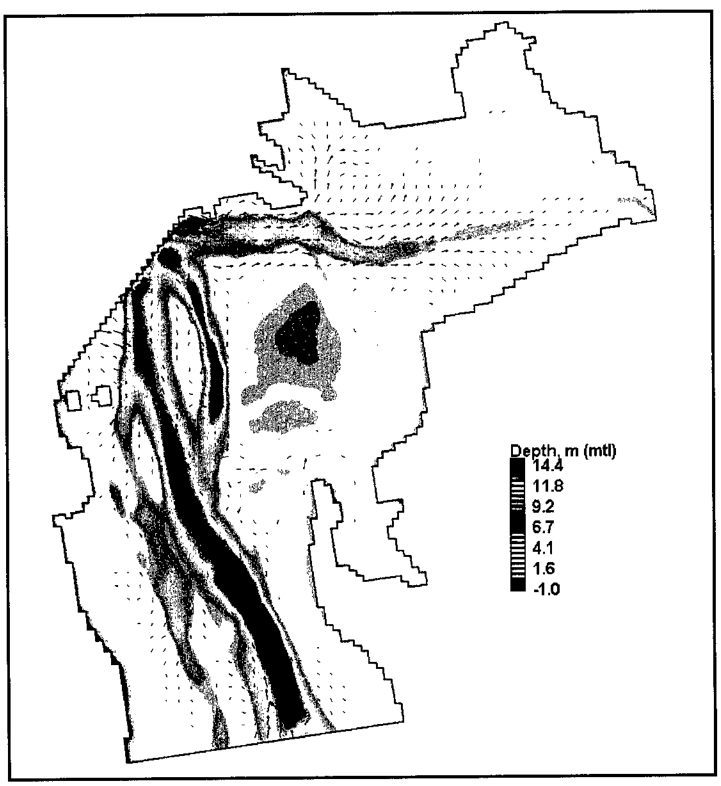


Figure 4-47. Velocity vectors on 17 November 2000 at 0800 (day of year 322.33)

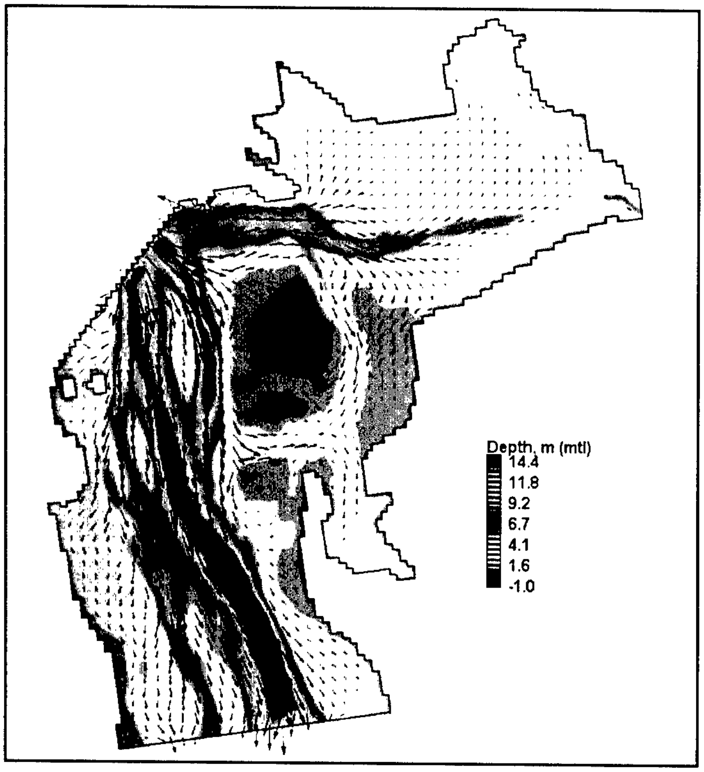


Figure 4-48. Velocity vectors on 17 November 2000 at 1200 (day of year 322.50)

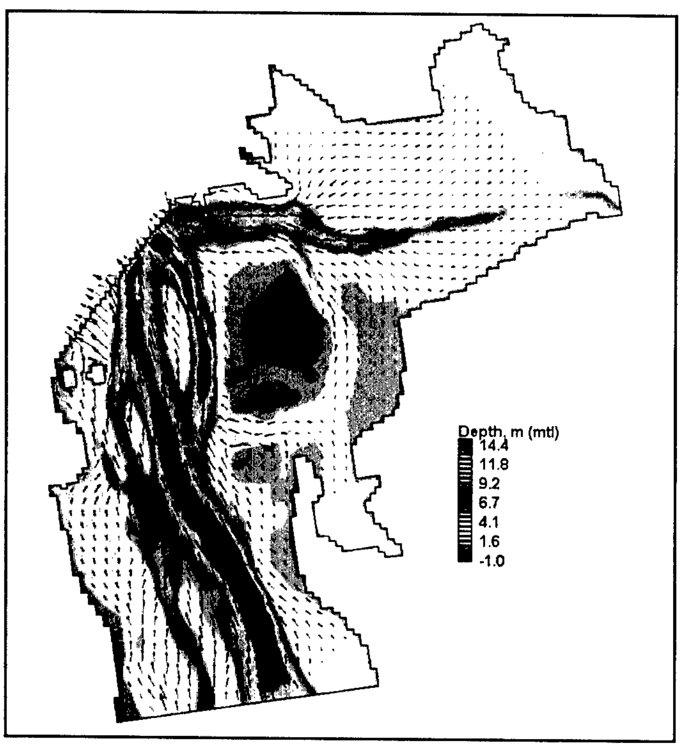


Figure 4-49. Velocity vectors on 17 November 2000 at 1600 (day of year 322.67)

Figure 4-49 shows the velocity at 1600 (day of year 322.67), a time when the tide is ebbing. Flow patterns are similar to those at 0400, although the velocities are weaker at 1600. Ellen Sands is mostly dry and the tidal flats north of the Willapa River are also partially dry.

The calculated tidal current at the Bay Center Entrance Channel over a 12-hr interval is shown in Figure 4-50 as a series of snapshots sampled every hour. The first snapshot is on 17 November 2000 at 0400 (day of year 322.17) when the current is ebbing. During the first 3 hr of the time sequence, the flow in the entrance channel ebbs strongly and little flow occurs on Ellen Sands or the South tidal flat. The southwest corner of Ellen Sands (directly north of the Bay Center Entrance Channel) has ebb flow that weakens over this 3-hr interval. Flow over the delta at the mouth of the channel changes orientation from northwest-directed to west-directed during this time.

During the second 3 hr, day of year 322.30 to 322.38, the tidal current is reversing from ebb to flood. Flow in the Bay Center channel is weak and reverses during this interval. The tidal flats remain dry during this time.

The 3 hr from day of year 22.42 to 322.50 are a time of increasing flood current. Flood velocities become stronger in the Bay Center Entrance Channel and water begins to inundate the tidal flats. Relatively strong flow develops over the southwestern Ellen Sands shoal, which may reduce the channelization of flow through the entrance channel during flood flow, thereby weakening the current through the channel and promoting sedimentation.

During the time interval from day of year 322.55 to 322.63, the last 3 hr of the time sequence, the tide is turning from flood to ebb. Velocities are weak, particularly in the Bay Center Entrance Channel. Weak currents occur over the Ellen Sands and South tidal flats.

Sediment transport modeling with M2D

A sediment total-transport algorithm was implemented within M2D to calculate the time variation in depth (or bottom elevation). The algorithm computes current-driven transport at a user-specified interval, which was 100 sec for this study. After each transport calculation, the change in depth is computed and the grid bathymetry is adjusted for erosion or deposition. The Watanabe formulation given by Equation 4-1 was implemented as a finite-difference approximation within M2D to compute change in depth.

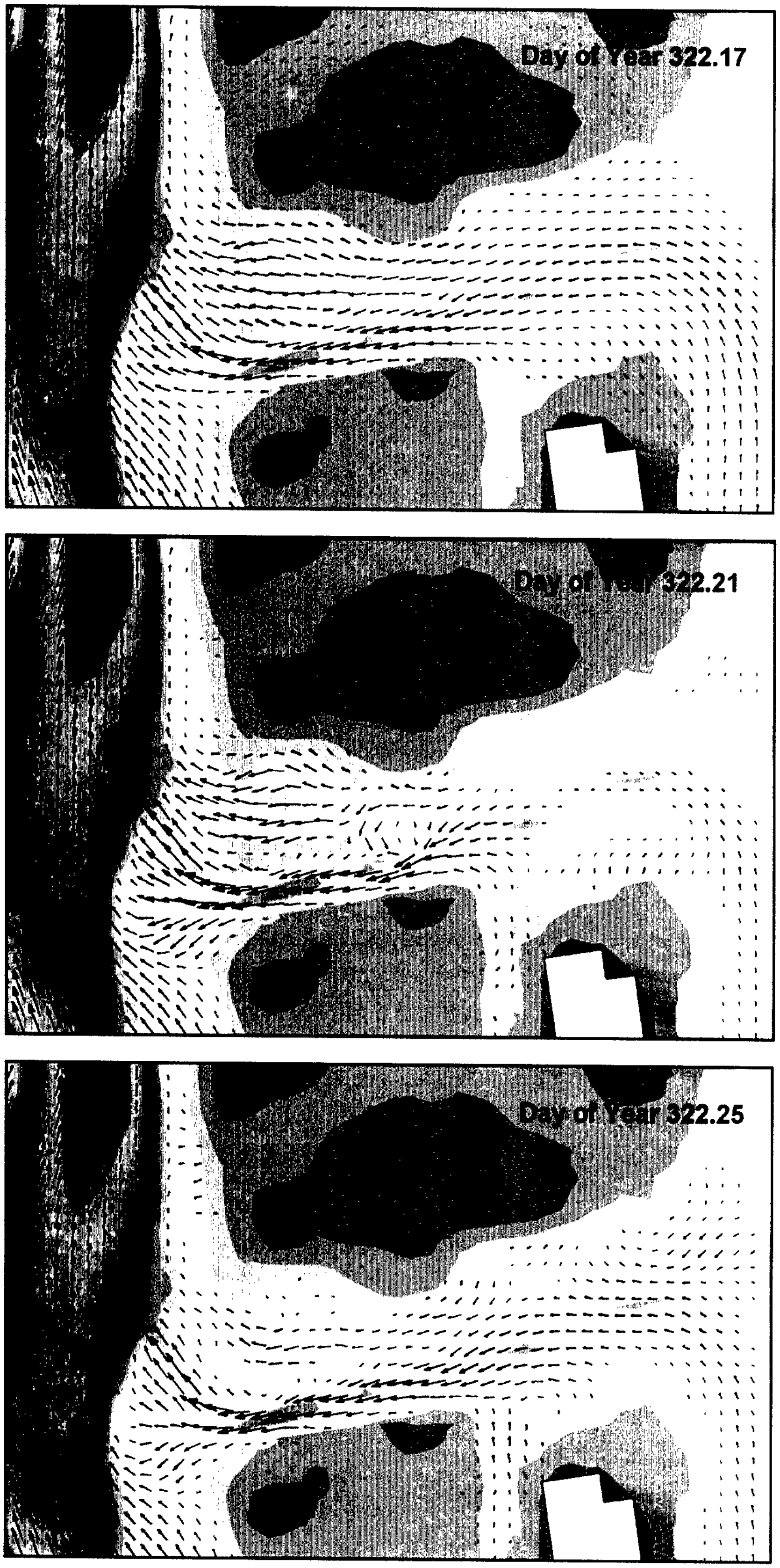
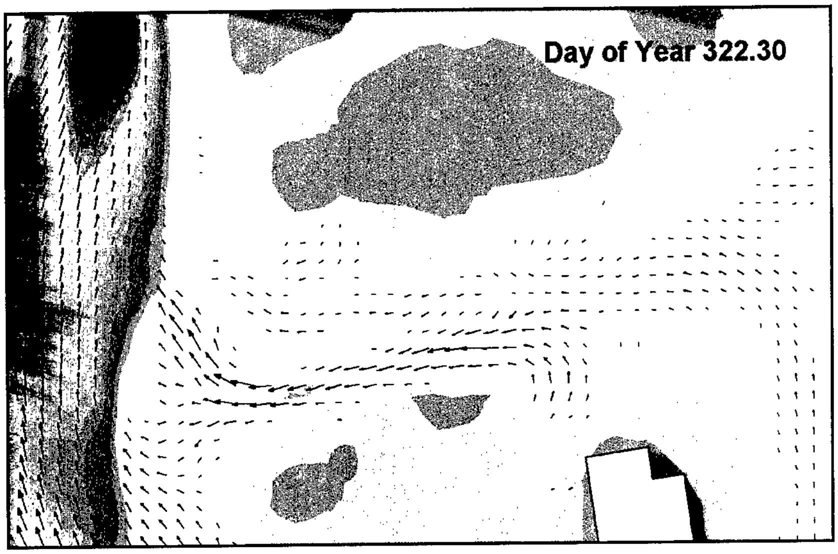
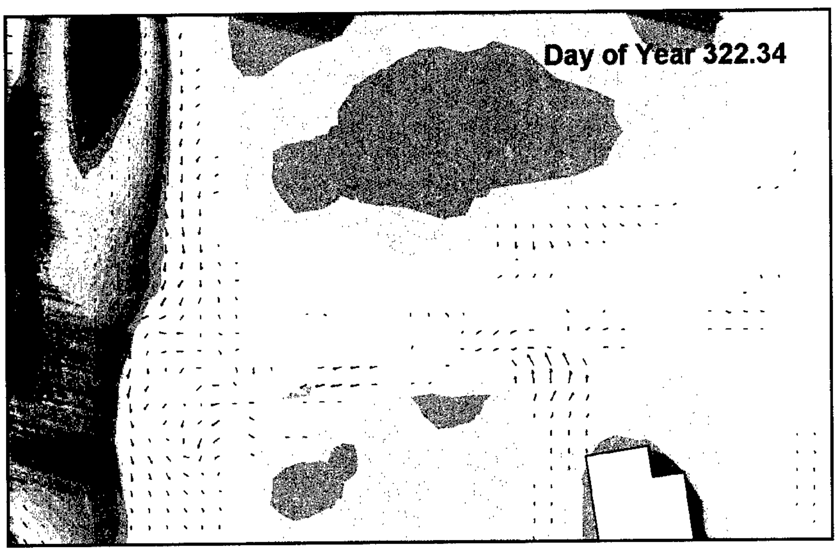


Figure 4-50. Velocity vectors at 1-hr intervals starting 17 November 2000 at 0400 (day of year 322.17) (Continued)





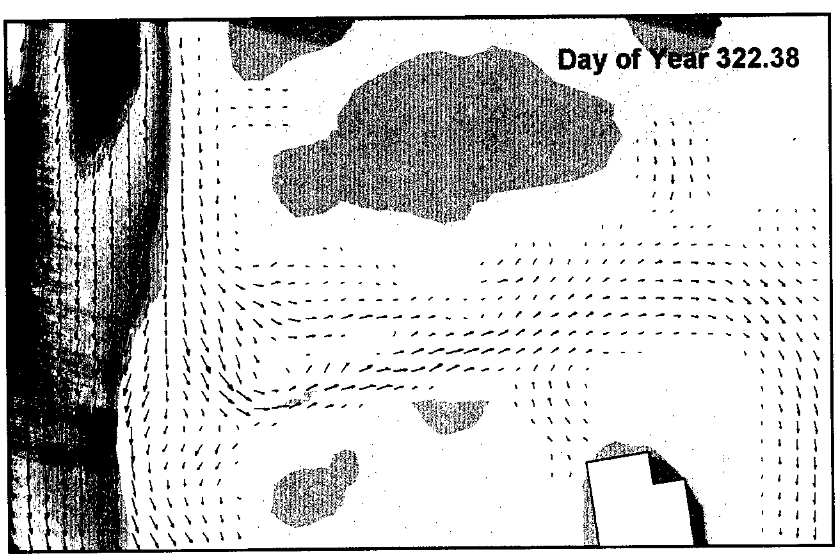


Figure 4-50. (Continued)

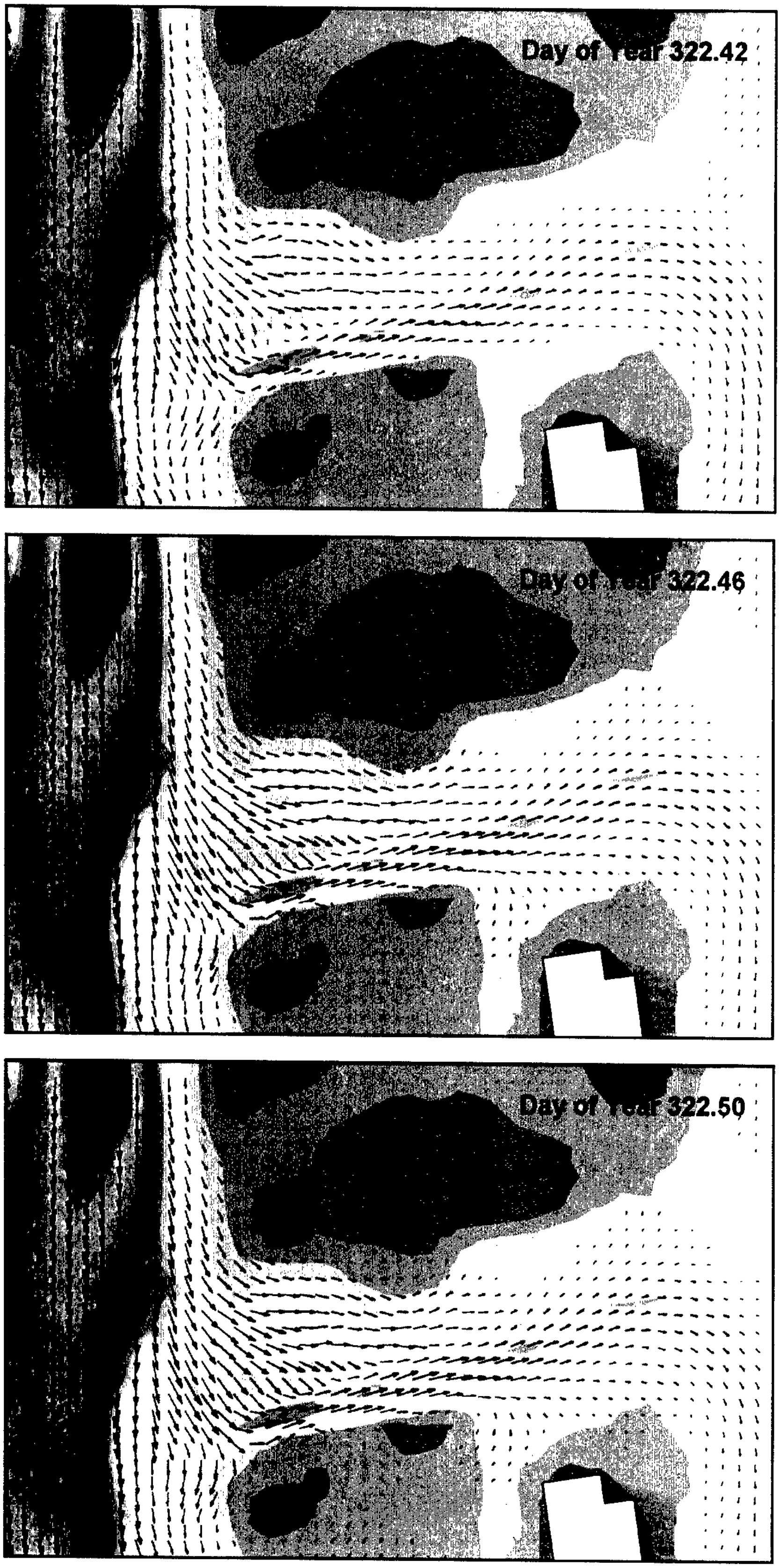


Figure 4-50. (Continued)

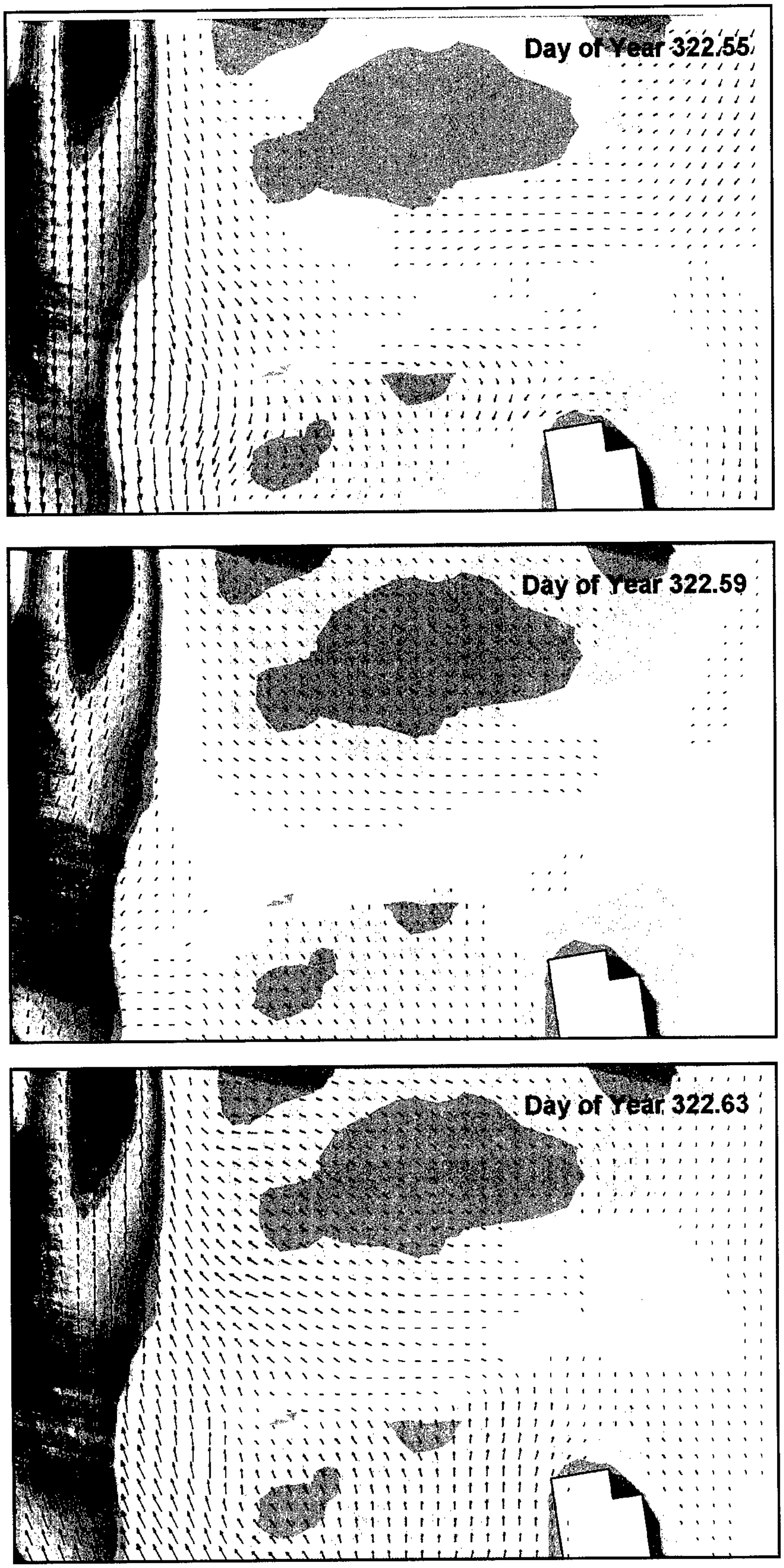


Figure 4-50. (Concluded)

Within M2D, the value of $C_{b\ max}$ in Equation 4-4 is determined for the time interval between the previous and present sediment transport calculation. Thus, $C_{b\ max}$ is the maximum value of the bottom-friction coefficient C_b over the time interval between sediment transport calculations and it is calculated at each cell. The bottom-friction coefficient C_b is calculated by

$$C_b = \frac{g}{\left(R^{1/6}/\mathrm{n}\right)^2}\left(1+\exp^{-\beta(h+\eta)}\right) \tag{4-5}$$

where

R = is the hydraulic radius

n = is the Manning roughness coefficient

β = is a scaling factor taken here to be 10

h = is the still-water depth

η = is the deviation from the still-water level

The exponential term increases the bottom-friction coefficient over shallow water.

Idealized evaluations

Two idealized evaluations of the sediment transport and bathymetry change calculations were conducted to verify that the solutions are realistic. Grain size for both tests was 0.2 mm. One evaluation specifies a one-dimensional channel with a trapezoidal trough in the center. The channel is 500 m long and described by 100 cells of 5 m on each side. The trench is 2 m deep over five cells relative to the still-water level (SWL). The sides of the trench slope between 1 and 2 m over three cells (i.e., depths of the three cells are less than 2 m and greater than 1 m). All other cells in the channel have a depth of 1 m relative to the SWL. The Manning roughness coefficient was set to 0.028 for all cells. A constant head difference of 0.03 m over the length of the channel was specified to drive a current along the channel. This head difference was achieved by setting the water levels at the end cells of the channel to 1 m and 0.97 m above the SWL, creating a flow in the positive x direction. Sediment was allowed to flow into and out of the grid. The simulation was run for 1,000 hr at a time-step of 100 sec. Sediment transport calculations were conducted at 100-sec intervals.

Evolution of the trench over time is shown in Figure 4-51. The trench fills from its left side, as expected with a right-directed current. The right side of the trench erodes over time. This combination results in trench shallowing and migration toward the right over the simulation interval. The behavior of the numerical solution is robust, with no unrealistic wiggles, mounds, or holes being generated. Figure 4-52 shows the normalized velocity along the channel with time. Maximum speed was 0.42 m/sec and occurred at cells having depth of 1 m (upstream and downstream velocity). Speed is not shown at time = 0 hr because

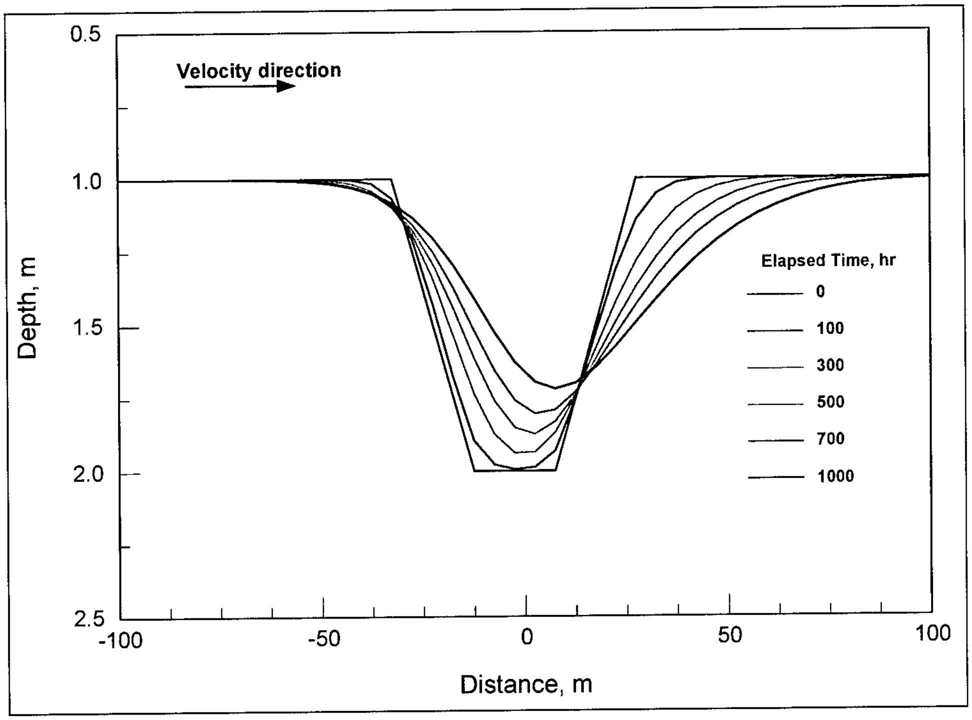


Figure 4-51. Trench test: Change in depth over 1,000 hr

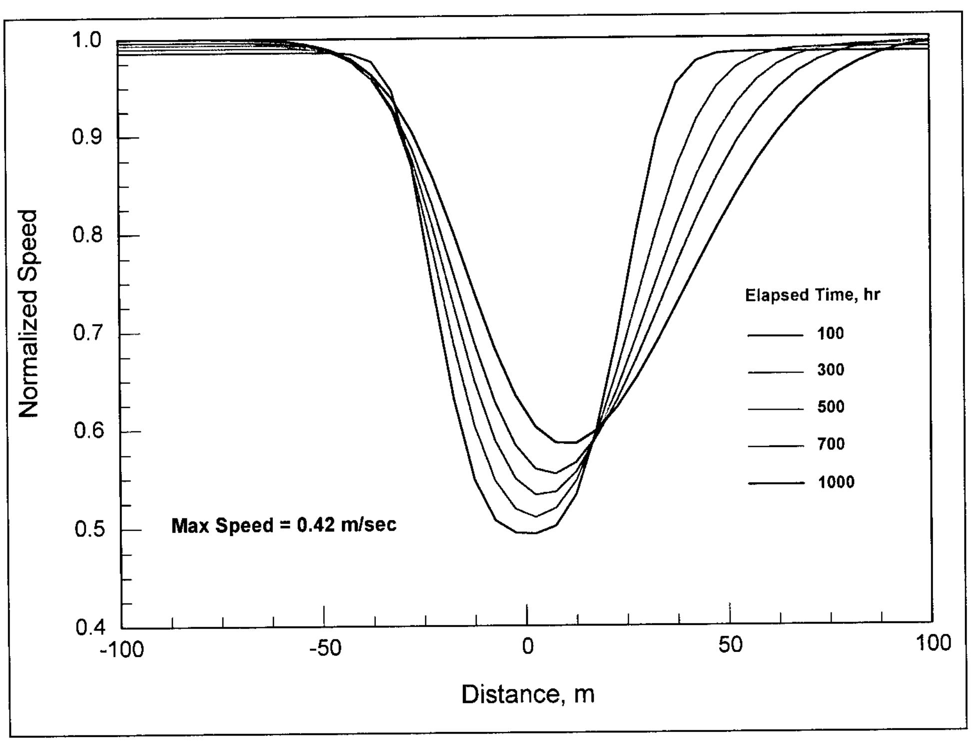


Figure 4-52. Trench test: Change in normalized current speed over 1,000 hr

the model was started from quiescent conditions and ramped to full forcing over 12 hr. The reduction in velocity over the trench decreases as the filling occurs, and it also migrates in response to trench movement. Thus, the model calculates both the sediment transport as a function of the current, and also the modification of the current by change in bathymetry.

A second evaluation was conducted in which a triangular mound was placed in the center of the channel. The peak of the mound was specified to be 0.5 m deep and the sides of the mound slope over four cells. The boundary conditions, friction factor, and time parameters were identical to the trench simulation. Evolution of the mound is shown in Figure 4-53. Over time, the top of the mound becomes more rounded as material is eroded. In addition, the mound is translated toward the right, in the direction of flow. As with the trench test, no artificial or unrealistic patterns are present in the solution, indicating that the numerical algorithm is robust. Figure 4-54 displays the normalized velocity along the channel with time. For the times shown, maximum speed was 0.60 m/sec and occurred at the peak of the mound at 100 hr. Speed increases over the peak of the mound, as expected. Over time, the location of maximum speed migrates with the mound. Thus, the feedback between the bathymetry and current is demonstrated.

Bay Center Entrance Channel simulations

Sediment transport modeling at Bay Center was conducted for the time interval 14 November through 20 December 2000 to correspond with dates of bathymetric surveys. In this simulation, sediment transport calculations were conducted every 100 sec, which included updating of the depth at each cell in the grid. To compare the measured and calculated change in bottom elevation, the measured bathymetry was mapped onto the M2D grid. This mapping made the comparison consistent for the grid resolution. Once the measured bathymetry from the two surveys was mapped to the grid, the difference between elevations was computed. Figure 4-55 shows contours of measured change in bottom elevation between the two surveys. Yellow and red contours denote accretion and blue contours denote erosion. Two black lines display the Bay Center Entrance Channel boundaries. Deposition occurred within the entrance channel and erosion took place to the west and to the south of the channel. This trend indicates a migration of the channel toward the west or southwest. The area of greatest deposition in the channel is near the bend, where 2.55 m accreted (over a cell size of 47.2 × 47.5 m). The greatest erosion that occurred west of the channel was 1.19 m (over a cell size of 40.6 × 44.7 m). Significant accretion also took place along the western and northwestern edge of the measurement area. Erosion occurred at the southernmost portion of the surveyed area (south of the channel).

Calculated change in bottom elevation is shown in Figure 4-56. Patterns that are similar to those measured are deposition in the Bay Center Entrance Channel, erosion to the west and south of the channel, accretion along the west and

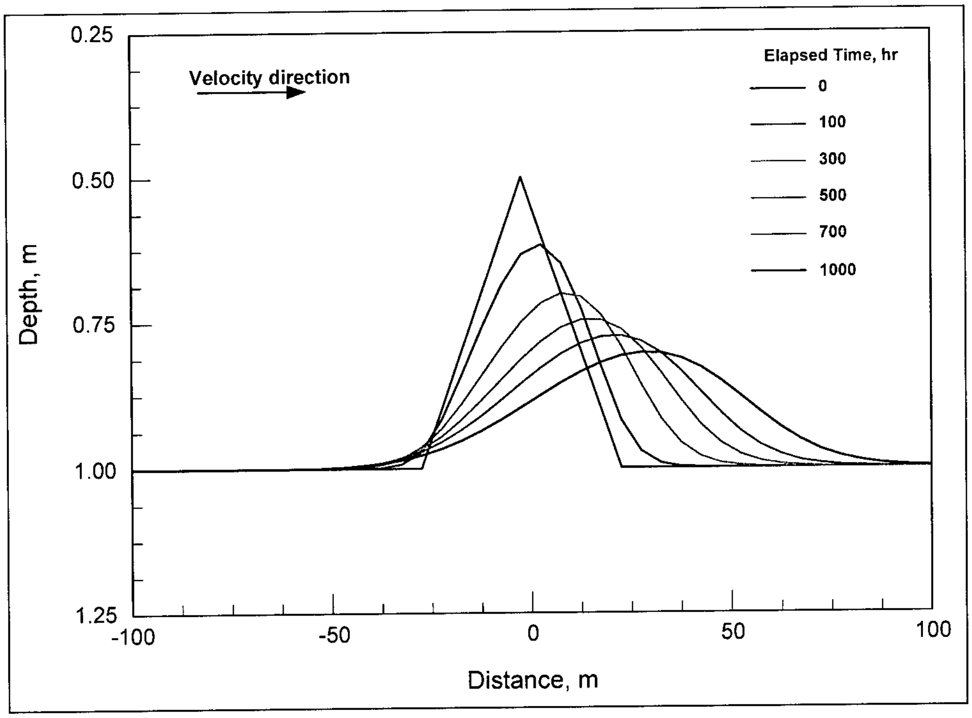


Figure 4-53. Mound test: Change in depth over 1,000 hr

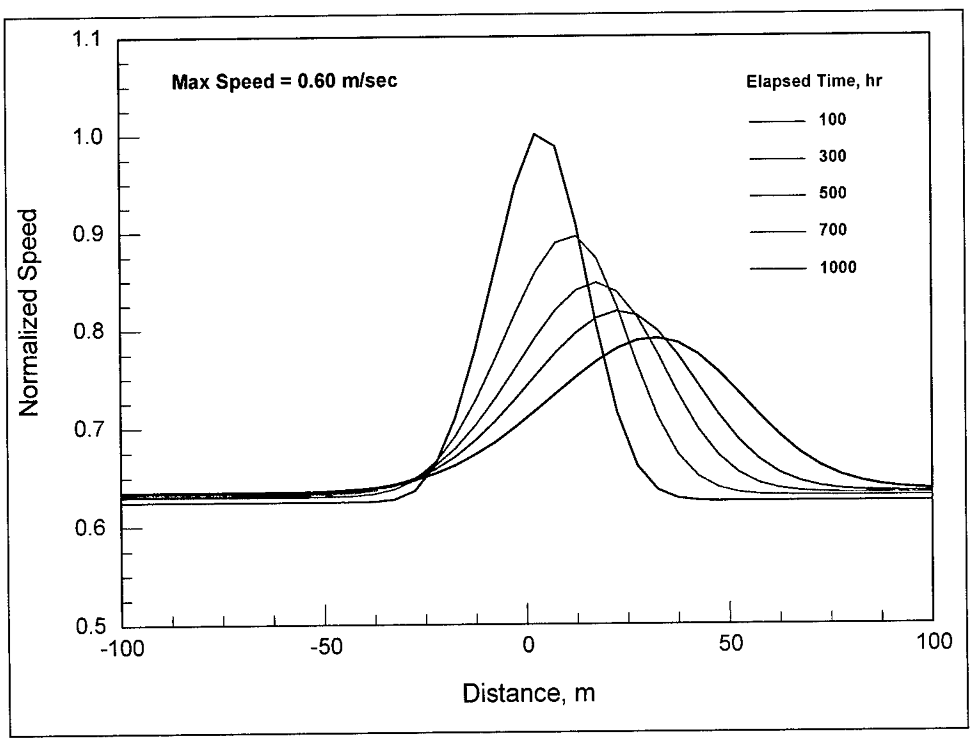


Figure 4-54. Mound test: Change in normalized current speed over 1,000 hr

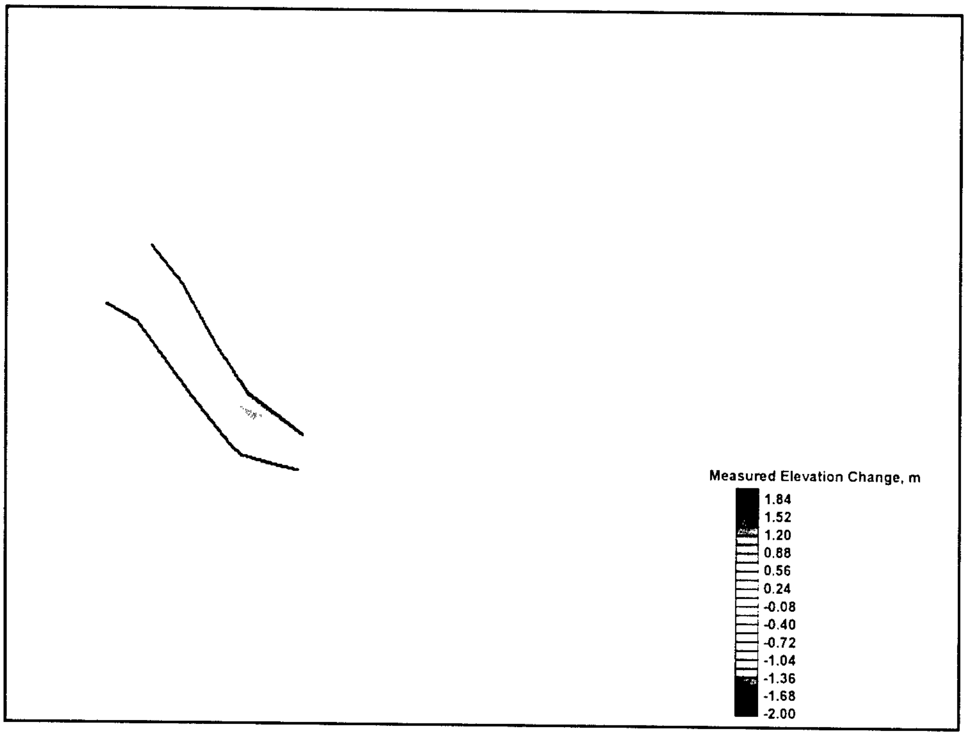


Figure 4-55. Measured change in elevation, 14 November to 20 December 2000

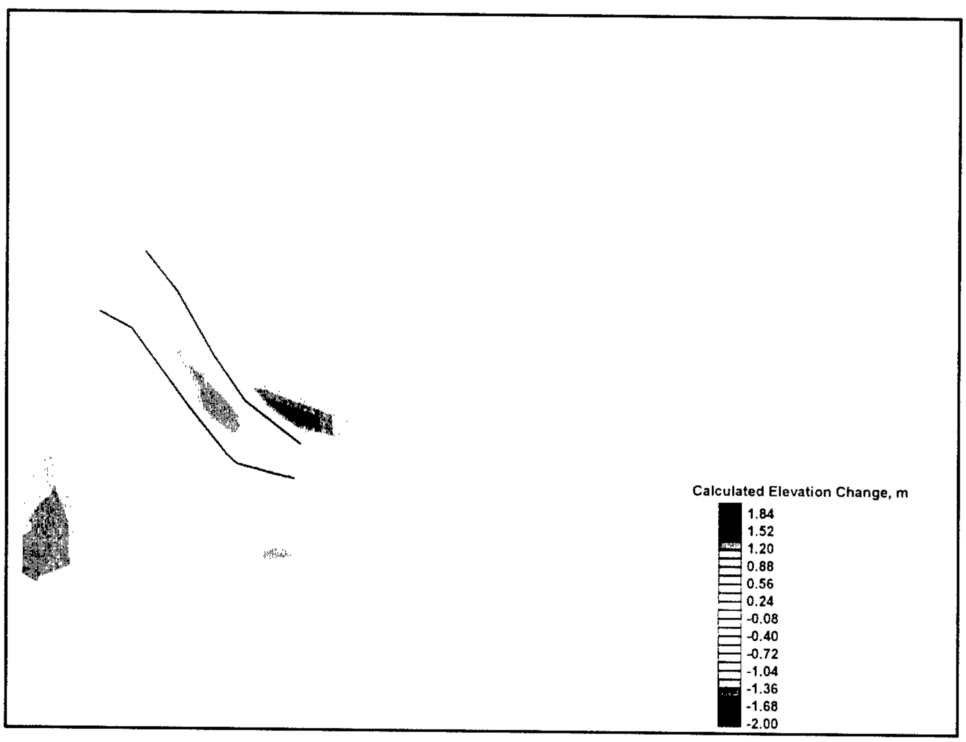


Figure 4-56. Calculated change in elevation, 14 November to 20 December 2000

northwest portion of the measurement area, and erosion at the southernmost section measured (south of the channel). Discrepancies between the calculated and measured elevation change are to the east of the channel and south and southeast of the bend in the channel. East of the channel, the model predicted significant erosion, which did not take place. To the south and southeast of the bend in the channel, the model predicted significant deposition, which was not seen in the measurements.

Within the Bay Center Entrance Channel, the calculated region of greatest deposition is shifted to the northwest, as compared to the measurements. The greatest elevation change calculated within the channel was 2.20 m, which is comparable to the 2.55 m that was measured. Similarly, the calculated area of greatest erosion directly adjacent and west of the channel is shifted to the northwest, as compared to the measurements. The greatest elevation change calculated for this area was erosion of 0.76 m, as compared to 1.19 m that was measured.

In the accretional area to the west and northwest of the Bay Center Entrance Channel, the calculated and measured changes agree fairly well. To the west, the greatest measured change was 1.37 m and the greatest calculated change was 1.18 m. These maximums occurred at adjacent cells on the numerical grid. At the bayward end of the channel near the more southern side, the measured accretion was 0.50 m and the calculated accretion was 0.53 m. These maximums also occurred at adjacent cells. Near the more northern end of the channel, measured accretion was 0.45 m and calculated was 1.08 m at the same cell. North of the channel end, the greatest measured change was 0.67 m and the greatest calculated change was 0.69 m. These maximums occurred at the same cell.

Along the southernmost portion of the measurement area that lies south of the channel, erosion was both measured and calculated. The areas of greatest erosion were measured at 0.64 m and calculated at 0.93 m. These maximums were located at adjacent cells.

The sediment transport calculations reasonably predict erosion and deposition in some areas and contain significant error in others. Sources of error may be inadequacies of the sediment transport formulation under certain hydraulic conditions, level of grid resolution, or inaccuracies in velocities (magnitude and/or direction) over some areas owing to lack of bathymetric data. In particular, elevations of the South tidal flat have been approximated in the model. The South tidal flat exerts control over water moving directly to the north and northwest. Thus, if the depths of the South tidal flat are incorrect, velocities near the flat will contain error, which, in turn, will produce error in the sediment transport calculations.

Conclusions for Bay Center modeling

Circulation modeling of the Bay Center Entrance Channel was conducted through a two-tiered approach that linked the regional model ADCIRC to the local model M2D. The ADCIRC model, developed for the Willapa entrance feasibility study was modified for calculations at Bay Center. An M2D grid was developed in which bathymetry identical to the ADCIRC mesh was specified.

Adjustments were made to elevations of the Ellen Sands and South tidal flat areas based on recent aerial photographs.

Water levels calculated by ADCIRC were applied as boundary forcing for M2D. Comparison of ADCIRC- and M2D-calculated water levels and velocities showed that the models generally agree, although there is some difference in the solutions. In particular, velocities on tidal flats are weaker as calculated by M2D than as calculated by ADCIRC. This difference in velocity computed by the two models probably owes to two sources: treatment of areas that wet and dry; and variation in representation of friction, both in friction factors and friction formulations.

A sediment transport algorithm was implemented within M2D and included calculation of change in bottom elevation over time. The sediment transport algorithm applied is that of Watanabe (1987). Deposition and erosion were reasonably represented by the sediment transport model within the Bay Center Entrance Channel, and to the north and west of the channel. In these areas, maximum erosion and deposition values computed from 14 November to 20 December 2000 were comparable. To the east and south of the channel, the calculated erosion and deposition did not compare well with that shown in the measurements. Two potential sources of error include lack of bathymetry data for the South tidal flat and insufficient grid resolution. Future work on the model will examine the sources of error.

The sediment transport model shows promise for calculation of channel infilling and morphology change at inlets. Tests of one-dimensional flow and transport for a mound and for a trough demonstrated correct behavior of the sediment transport model. Over time, the mound height decreased and the crest propagated in the direction of the current. In the trench test, the trench filled and the downstream bank eroded. For both tests, no irregularities were found in the solutions. Application at a control site, such as Bay Center, gives confidence in model calculations in a realistic wave, tidal hydraulic, and transport regime with complex bathymetry.

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5 Environmental Review and Permitting[1]

Introduction

The information provided in this chapter corresponds to the action alternatives that remain viable after the engineering analyses in the previous chapters. The purpose of this chapter is to evaluate the alternatives in the context of the current environmental review and permitting processes and to assist in determining whether advance biological studies may be required. Time lines for the review and permitting of the alternatives are also included in this chapter.

The action alternatives are categorized by location into two groups: North Fairway (3A, 3B), and North Fairway/SR-105 (3H-a, 3H-b). Appendix H of Report 1 (Kraus 2000) identified dredged material disposal site alternatives for each action alternative. The North Fairway options all consider disposal site alternatives A, B, C, D, D1 and E. The "no action" alternative is the continuation of the survey of the channel to locate and mark the deepest areas for navigational purposes and to obtain data for continuing analysis of the remaining alternatives.

Information in this chapter is not intended to substitute for the alternatives analyses required by the National Environmental Policy Act (NEPA) and the Clean Water Act. A general discussion of the environmental review and permitting requirements will be presented for the four alternatives; specific application of these requirements will then be discussed under each alternative. The discussions will also include constraints and opportunities attributable to each alternative. As the status quo, the "no action" alternative will not require further environmental review in this chapter. The findings are reported in a matrix and in projected time lines for the permitting and environmental review processes.

Environmental Review

Major projects require Federal, state, and local environmental review to analyze project impacts to the natural and built environments. These analyses occur under the requirements and guidance of the NEPA and, in Washington, the State Environmental Policy Act (SEPA). (SEPA is codified in the Washington Administrative Code (WAC) 197-11.) Environmental review is a process and

[1] Written by Lennie Rae Cooke, Pacific International Engineering[PLLC], Edmonds, WA.

does not result in the issuance of a permit. NEPA and SEPA require analysis of the potential impacts of a project, a description of how those impacts will be minimized, and public input to the final decision. For Federal actions,[1] compliance with NEPA satisfies the state's SEPA requirements.

There are three basic questions common to both NEPA and SEPA. First, is the proposed project subject to either or both statutes? Generally, if the project does not fall into the categorical exclusion (NEPA) or categorical exemption (SEPA) categories, the statutes apply. Second, will the project result in a probable significant adverse environmental impact? If the responsible official (in this case, the Environmental Resources Section in the Seattle District) determines, after completion of an Environmental Assessment (EA), that the project will have such impacts, the District must prepare an environmental impact statement (EIS). Third, what elements of the natural and built environment are adversely affected by the project and must be included in the EIS? The answer to this question determines the scope of the EIS.

National Environmental Policy Act 40 CFR 1508

Purpose of act

NEPA was signed in January 1970 as the "national charter for protection of the environment" (40 CFR Part 1500.1), and was enacted to ensure that information about the environmental impact of any Federal action is available to public officials and citizens before decisions are made and before actions are taken. Under NEPA, Federal agencies are directed to integrate the natural and social sciences, environmental amenities and values, and design arts with economic and technical considerations in the planning and decision-making process. NEPA is a broad-reaching mandate for Federal agencies to work together with state, local, and tribal governments, public and private organizations, and the public, to achieve and balance national social, economic, and environmental goals, while accomplishing their missions. Federal agencies are required to integrate the NEPA process with other planning at the earliest possible time to ensure that planning and decisions reflect environmental values, to avoid delays later in the process, and to head off potential conflicts.

Process

Even if the Corps of Engineers District project falls into the categorical exclusion category under NEPA,[2] further review is required by the District to address all other applicable Federal laws, such as the Endangered Species Act (ESA) and the Coastal Zone Management Act (CZMA). If the project is not categorically excluded, an EA is prepared. If no potential impacts are identified in the EA, a Finding of No Significant Impact (FONSI) is issued. The EA is prepared in conjunction with other necessary documents, such as the alternatives

[1] Federal actions are those initiated by Federal agencies or projects that include Federal funding.
[2] Categorical exclusions for the Corps of Engineers are listed in 33 CFR 230.9.

analysis required under Section 404 of the Clean Water Act. The EA is generally prepared after the comment period for the public notice of the permit application has expired and must be finished prior to the completion of the Statement of Finding (SOF).[1] The SOF and FONSI are signed by the District Engineer.

The EA considers the impacts to cultural, environmental, and biological resources, and it determines whether an EIS is necessary. The resources analyzed in the EA are project-specific; the contents may differ from project to project. The Corps District prepares a preliminary EA including an area map, vicinity map, site plan, maps depicting the environmental setting, discipline reports, and any agency coordination letters such as endangered species listings, prime and unique farmland determinations, archaeological/ historic reports, etc. If the EA determines that the proposal may have significant environmental impact, the proposal is re-evaluated to determine whether the significant impact can be mitigated or eliminated. If the impact cannot be eliminated, an EIS is required.

If the results of the EA analysis determine that an EIS is necessary, the EA will guide the scope of the EIS, directing the focus of the EIS on those potential impacts to existing resources. The EIS primarily contains: an identification of the alternatives (no action, preferred action, and other reasonable actions); a discussion of the environmental consequences for each alternative; and mitigation or other actions that may be taken to decrease the environmental consequences of the proposal. The draft EIS is distributed to the public for comment and, after comment, the Final EIS (FEIS) is prepared and filed. Thirty days after the FEIS is filed and published in the *Federal Register*, the SOF, called a Record of Decision if an EIS is required, is signed, and the environmental review is complete.

WAC 197-11-610 allows an agency to adopt environmental analysis prepared under NEPA to satisfy SEPA requirements. In general, a NEPA EA may be adopted to satisfy requirements for a SEPA determination of nonsignificance (DNS) or mitigated determination of nonsignificance (MDNS), and a NEPA EIS may be adopted as a substitute for a SEPA EIS. Federal documents may also be incorporated by reference as support for issuance of a SEPA document as allowed by WAC 197-11-635. If an EIS is required under both NEPA and SEPA, a joint EIS may be prepared to reduce the amount of paperwork. This allows the SEPA lead agency to offer input into the EIS preparation and ensure that the information needed to evaluate state and local permits is included in the EIS.

Table 5-1 illustrates the environmental review process, participants, and documentation, and compares the NEPA and SEPA requirements.

Federal, State, and Local Environmental Permit Requirements

Federal, state, and local regulations are written to protect environmental quality and resources, and to regulate the type and extent of development activities. Typically, the required permits for dredging projects are issued by the

[1] The SOF is issued for projects that do not require an EIS.

Corps, the state, and local jurisdictions. Federal agencies are required to obtain Federal, state, and local permits where Congress has made a clear waiver of sovereign immunity. There are certain Federal laws that do contain such waivers and which require Federal agencies to comply with state or local laws. These include certain permits and approvals in the Clean Water Act, a limited waiver in the Coastal Zone Management Act, and compliance with the Endangered Species Act as discussed in the following paragraphs.

Table 5-1
Comparison of NEPA and SEPA Processes

Federal	State of Washington
Lead Agency: Federal (some state agencies)	Lead Agency: State or local
Categorical Exclusions	Categorical exemptions
Environmental Assessment (EA)	Environmental check list
Finding of No Significant Impact (FONSI) or Notice of Intent (NOI)	Determination of Nonsignificance (DNS) or Determination of Significance and Scoping Notice (DS/SN)
NOI published in *Federal Register*	DNS, DS/SN published in *SEPA Register*
Public Scoping, meeting optional	Public Scoping, meeting optional
Prepare Draft EIS	Prepare draft EIS
Draft EIS Notice of Availability published in *Federal Register*	Draft EIS Notice published in *State Register*
Public Review 45 to 60 days	Public Review 30 to 45 days
Prepare Final EIS (FEIS)	Prepare FEIS
FEIS Notice of Availability published in *Federal Register*	FEIS Notice published in *State Register*
30-day waiting period	7-day waiting period
Record of Decision (ROD) published in *Federal Register*	Notice of Action Taken (NAT) (optional)
Agency action may proceed (pending receipt of all applicable permits)	Agency action may proceed (pending receipt of all applicable permits)

In those cases where the Corps District is coordinating Federal operations and maintenance (O&M) activities, a Corps permit is not issued; however, the public notice coordination is thorough and complete with approvals sought from local and state agencies. Typically, the approvals consist of State of Washington 401 Water Quality Certification including Water Quality Modification with an Advisory Hydraulic Project Approval (HPA) from the Washington State Department of Fisheries and Wildlife (WDFW). In Washington, the local project sponsor will obtain the Shoreline Substantial Development Permit (SSDP) as a local sponsor requirement.

The U.S. Environmental Protection Agency (EPA) and to some extent, the Corps, has authorized the State of Washington to administer some Federal permits, such as the 401 Water Quality Certification (WQC) required by the Clean Water Act. The Determination of Consistency with the Federal Coastal Zone Management (CZM) Act has been delegated to the state by the National Oceanic and Atmospheric Administration (NOAA). For Corps-sponsored projects, the 401 WQC is obtained from the Washington Department of Ecology

(WDOE). For Federal O&M activities, the Corps completes a CZM Consistency Determination that is provided to WDOE for concurrence.

The Seattle District must adhere to the requirements imposed by certain Federal laws that cut across all Federal programs. These cross-cutting laws and applicable state regulations are discussed in the following paragraphs.

Rivers and Harbors Act, 33 USC Section 403

The 1899 Rivers and Harbors Act prohibits unauthorized activities that obstruct or alter a navigable waterway. Specifically, Section 10 of this act applies to any dredging and/or disposal activity in navigable waters of the United States, which includes Willapa Bay. A Section 10 permit triggers consultation with the National Marine Fisheries Service (NMFS) and the U.S. Fish and Wildlife Service (USFWS) regarding project impacts to threatened and endangered species and designated critical habitat that are found or may be found in the project action area. The Corps District is required to undergo consultation and obtain concurrence from these sources for dredging and disposal projects.

Clean Water Act, 33 USC Section 1251 *et seq.*

Section 404. Section 404 of the Clean Water Act (CWA) is jointly administered by the Corps of Engineers and the EPA to regulate the direct or indirect discharge of pollutants into waters of the United States. Discharges of dredged or fill material into navigable waters of the United States are regulated under Sections 401 and 404 of the CWA. Under the Section 404(b)(1) "Guidelines," (40 CFR 230.10(b)), no such discharge shall be allowed if it:

a. Causes or contributes to violations of any additional state water quality standard, pursuant to Section 401 of the CWA, after consideration of disposal site dilution and dispersion.

b. Violates any applicable toxic effluent standard or discharge prohibition under Section 307 of the CWA.

c. Jeopardizes the continued existence of any endangered or threatened species, or contributes to the destruction or modification of any critical habitat for such species.

d. Violates any requirement imposed by the Secretary of Commerce to protect any marine sanctuary.

A Section 404 permit requires an analysis of the project alternatives to determine if there are any "practicable" alternatives to the discharge. The Section 404(b)(1) alternatives analysis evaluates the alternatives by first looking at avoiding the impact (no discharge), then at minimizing the impact, and finally at compensatory mitigation. Mitigation is developed through the guidelines established in the Memorandum of Agreement between the EPA and the Corps.

Section 401. A Section 401 WQC is required from the State of Washington before a Federal permit may be issued to conduct any activity that may result in any discharge into surface waters. This includes discharge of dredged and fill material into water or wetlands. Many excavation activities that occur in

streams, wetlands, or other waters of the state also require a Section 401 certification. Through this process, the WDOE works with applicants to ensure that projects do not degrade these environmental resources.

In Washington State, the WDOE issues the WQC. This certificate usually includes Water Quality Modification with an Advisory Hydraulic Project Approval from the Washington State Department of Fish and Wildlife (WDFW). (It is the Corps' position that the HPA is not enforceable since there is no waiver of sovereign immunity for this particular approval. However, as a general rule, the Corps evaluates the conditions listed in the advisory HPA and determines whether, from an environmental standpoint, the conditions are warranted. The Corps discusses the listed conditions with WDFW if not believed to be warranted.)

The Federal agency (the Corps) is provided with a WQC from WDOE stating that the discharge complies with the discharge requirements of Federal law and with the aquatic protection requirements of state law. Public notice (21-day) for a WQC is included with the Corps' public notice of the project.

Endangered Species Act, 16 USC 1531, *et seq.*

Section 7(a) of the Endangered Species Act (ESA) requires consultation with NMFS and USFWS (collectively, the Services) on any action that is likely to affect the continued existence of any proposed species or result in the destruction or adverse modification of any critical habitat.

The purpose of the ESA is to ensure that Federal agencies use their authorities to protect and conserve endangered and threatened species. If the Services determine that a proposed action would likely have a negative impact, then the project will be stopped unless the consulting parties can agree on alternatives to eliminate jeopardy. If there are no feasible alternatives that can be carried out, the action agency may apply for an exemption with the Endangered Species Committee.

The Seattle District is required to consult with the Services before dredging and disposal for the Willapa Bay Navigation Project can occur. Informal consultation requires assessment of effect for projects. In June 2000, the Seattle District submitted a Programmatic Biological Assessment (PBA) to the Services for the proposed use of two disposal sites (at Cape Shoalwater and Goose Point), Washington Department of Natural Resources-managed, unconfined open-water sites. The consultation with the Services on the PBA is complete and the concurrence letters have been received. NMFS determined that open-water disposal of clean dredged material does not jeopardize the continued existence of threatened species. The PBA gives descriptions of the existing conditions, the methods anticipated for all authorized areas where dredging and disposal occurs, and the impacts on the threatened, endangered, and candidate species within the geographic area affected by the project. The PBA does not, however, cover the proposed projects or dredged-material disposal areas contemplated in this report. Therefore, the Seattle District would need to reinitiate consultation (either formal or informal) to address potential effects from new actions.

Sustainable Fisheries Act of 1996, Public Law 104-267

This act amended the Magnuson-Stevens Act, which regulates fishing in United States waters, to establish new requirements for "Essential Fish Habitat" (EFH) descriptions in Federal Fishery Management Plans (FMPs) and to require Federal agencies to consult with NMFS on activities that would adversely affect EFH. The Pacific States Fishery Management Council amended the Pacific Groundfish Fishery Management Plan and the Coastal Pelagic Species Management Plan to designate waters and substrate necessary for spawning, breeding, feeding, and growth of commercially important fish species.

The marine extent of groundfish and coastal pelagic EFH includes those waters from the nearshore and tidal submerged environments within Washington, Oregon, and California state territorial waters out to the exclusive economic zone (370.4 km) offshore between the Canadian border to the north and the Mexican border to the south.

There are seven composite EFHs: estuarine, rocky shelf, non-rocky shelf, canyon, continental shelf/basin, neritic, and oceanic habitats. The action alternatives presented here occur exclusively over sandy bottoms within Willapa Bay and, therefore, potential impacts would fall under the estuarine composite EFH.

As part of the consultation with NMFS, the Seattle District would describe the effects on EFH of dredging and disposal, including project methods, location, species, conservation measures, and effects determinations. NMFS may choose to include additional conservation measures.

Coastal Zone Management Act, 16 U.S.C. Section 1451 *et seq.*

The Coastal Zone Management Act (CZMA) requires that Federal agencies be consistent with the enforceable policies of state coastal zone management programs when conducting or supporting activities that affect a coastal zone. It is intended to ensure that Federal activities are consistent with state programs for the protection and, where possible, enhancement of the nation's coastal zones. As defined in the CZMA, the coastal zone includes coastal waters extending to the outer limit of state submerged land title and ownership, and adjacent shorelines (typically 200 ft landward of ordinary high water) and land extending inward to the extent necessary to control shorelines. The coastal zone includes islands, beaches, transitional and intertidal areas, salt marshes, etc.

To comply with the CZMA, the Federal agency must identify activities that would affect the coastal zone, including development projects. If an activity would affect the coastal zone, the Federal agency must review the state coastal zone management plan to determine whether the activity would be consistent with the plan and then notify the state of its determination. Federal agencies must prepare a written consistency determination which includes: a detailed description of the action, its associated facilities, and coastal zone effects; a brief statement on how the activity would be consistent with the state coastal zone management plan; and data to support the consistency determination. The CZM Consistency Determination is based on the Corps' determination that the project complies with the policies, general conditions, and activities as specified in the Shoreline Management master program adopted by the local jurisdiction.

The state is required to respond to the consistency determinations. If WDOE disagrees with the determination, it will respond with its reasons for disagreeing, along with supporting documentation and recommended alternatives that can be undertaken to allow the activity to proceed, consistent with the management program.

If a conflict arises between the state and the Federal agency over how a Federal undertaking should proceed, there are several approaches that can be taken to resolve the conflict, including informal discussions between the parties with the assistance of NOAA, if requested; mediation by the Secretary of Commerce with public hearings; and judicial review.

National Historic Preservation Act, 16 U.S.C. 470

The National Historic Preservation Act (NHPA), as amended, directs Federal agencies to integrate historic preservation into all activities which either directly or indirectly involve land use decisions, to ensure Federal leadership in the preservation of prehistoric and historic resources of the United States.

Before approving or carrying out a Federal, Federally assisted, or Federally licensed undertaking, Section 106 of the NHPA requires Federal agencies to take into consideration the impact that the action may have on historic properties which are included on, or are eligible for inclusion on, the National Register of Historic Places. Section 106 also requires that Federal agencies provide the Advisory Council on Historic Preservation (ACHP) with the opportunity to comment on the undertaking.

In fulfilling the requirements of Section 106 and its implementing regulations, Federal agencies are required to:

a. Identify and evaluate any historic properties that might be impacted by the undertaking.

b. Determine the effect of the undertaking on these properties.

c. Develop alternatives and measures to avoid or mitigate adverse effects. Agencies may find it necessary to carry out a cultural resource survey in connection with the Section 106 review process. The Section 106 review process is usually carried out as part of a formal consultation with the State Historical Preservation Office (SHPO), the ACHP, and any other parties, such as Indian tribes that have knowledge of, or a particular interest in, historic resources in the project area of the undertaking.

Marine Protection, Research, and Sanctuaries Act, 33 U.S.C. 1441-1445

The Marine Protection, Research, and Sanctuaries Act, as amended, authorizes research and monitoring related to ocean dumping as well as research on possible effects of pollution, overfishing, and human-induced changes of the ocean system. The EPA, working with the Corps, shall develop alternative disposal methods and determine the means of minimizing impacts on human health, welfare, or amenities, or the marine environment, ecological systems, or economic potentialities.

The EPA assesses the feasibility of the disposal of dredged material into ocean waters. Plans should integrate, where appropriate, Federal, state, regional, and local waste disposal activities into a comprehensive regional disposal strategy. These plans should address, among other things:

a. The sources, quantities, and types of materials that require and will require disposal.

b. The environmental, economic, social, and human health factors (and the methods used to assess these factors) associated with disposal alternatives.

c. The improvements in production processes, methods of disposal, and recycling to reduce the adverse effects associated with such disposal alternatives.

d. The applicable laws and regulations governing waste disposal.

e. Improvements in permitting processes to reduce administrative burdens.

Fish and Wildlife Coordination Act, 16 U.S.C. 661 *et seq.*

The Fish and Wildlife Coordination Act (FWCA), as amended in 1964, was enacted to protect fish and wildlife when Federal actions result in the control or modification of a natural stream or body of water. The statute requires Federal agencies to take into consideration the effect that water-related projects would have on fish and wildlife resources, take action to prevent loss or damage to these resources, and provide for the development and improvement of these resources. The FWCA is administered by the Services.

To comply with the requirements laid out in the statute, Federal agencies must first determine whether a proposed activity will result in the control or modification of a body of water. Typical actions that would fall under the jurisdiction of the FWCA include:

a. Discharge of pollutants including industrial, mining, and municipal wastes, or dredged and fill material into a body of water or wetlands.

b. Projects involving construction of dams, levees, impoundments, stream relocation, and water-diversion structures.

If a project to be constructed, licensed, or permitted by a Federal agency would involve any of these activities or any other activity resulting in the control or modification of any water body for any purpose, then the Federal agency must consult with the Services to develop measures to mitigate project-related losses of fish and wildlife resources. Where possible, the action agency must incorporate the recommendations in the project plans. The constructing, licensing, or permitting Federal agency is to include in the project plans such justifiable means and measures as it finds should be adopted to obtain maximum overall project benefits.

Washington Department of Natural Resources

The DNR manages aquatic lands on behalf of Washington State. As a general rule, anyone wishing to use Washington State-owned aquatic lands (including harbors, state tidelands, shorelands, and beds of navigable waters) must obtain authorization from the DNR. Examples of activities that require an authorization are marinas, docks, and similar land/water connectors, shellfish/aquaculture leases, geoduck harvest sales, dredged material disposal, easements for bridges and utility crossings (including outfalls), and sand and gravel removal. Fees are variable and negotiable. Additional fee information for use of dredged material disposal sites is found in the Revised Code of Washington 79.90. Corps of Engineers navigation projects are exempt from DNR's dredged-material disposal site use authorization requirements.

Discussion

Application of the environmental documentation requirements specifically to the project alternatives are discussed in the following paragraphs. Permits required for project implementation are listed for each alternative, as are the known permitting constraints. Opportunities to carry out project elements in ways to create a positive environmental effect are presented.

North Fairway

Description of North Fairway alternatives. The construction activities of the two alternatives in the North Fairway are dredging and disposal of the dredged material. The dredging operation will occur primarily on the entrance bar. The North Fairway dredging alternatives are combined with disposal site Alternatives A, B, C, D, D1, and E. Basic descriptions of the variations of dredging the North Fairway channel are given in Table 5-2.

Table 5-2
North Fairway Dredging Options

Alternative	Dredging Options
3A	Dredge a straight 26-ft-deep by 500-ft-wide channel at its northernmost location.
3B	Dredge a 26-ft-deep by 500-ft-wide migrating channel, with a minimum 1,500-ft width in the S-curve.

Environmental review. The Seattle District will prepare a NEPA EA for the preferred action alternative. The primary factors to be evaluated for impacts to the environment from the project are impacts to species and habitat within the Action Area.[1] The sediment dredged from the North Fairway is believed to be suitable for open-water disposal, as well as for the beneficial use of beach nourishment.

[1] Action Area is the geographic area within which impacts from the dredging or disposal activities may affect listed or proposed species.

Permitting process. The following approvals and permits must be obtained prior to Federal dredging and disposal:

a. EA (leading to FONSI or FEIS).

b. 404(b)(1) alternatives analysis to be completed by the Environmental Resources Section of the Seattle District.

c. ESA Section 7 consultation with the Services for dredging and disposal Biological Assessment (BA) alternatives.

d. 401 Water Quality Certification (WQC) / Water Quality Modification (WQM) from the WDOE.

e. CZM Consistency Determination with concurrence from the WDCOE.

f. State Response Letter comments from WDFW in the form of an Advisory HPA is usually received but is not required. The Advisory HPA may be attached to the 401 WQC.

g. EPA 401 WQC is required if the proposed dredging includes disposal on treaty tribal lands; however, disposal sites proposed for the current project are not located on any treaty lands.

Constraints and opportunities. Constraints to these alternatives are primarily driven by ESA and sensitive species concerns. Sensitive species and habitats in Willapa Bay have been identified as harbor seals and their haul outs and pupping areas, gulls and terns and their breeding areas, and brown pelicans and their roosting areas. There are also intertidal habitats (eelgrass, wetlands, and mud flats) within the area, as well as snowy plover habitat (sand dunes). Migrating adult and juvenile salmon utilize Willapa Bay, and herring spawn in some portions. Crab are present in intertidal areas. Razor clams support a commercial enterprise in the bay.

Direct impacts to species include mortality or stress from noise, entrainment, turbidity, decrease of dissolved oxygen, and coverage by disposal material. Indirect impacts include reduction of food availability and disturbance during nesting season. Mitigation is likely to be required for any impacts caused to crab by hopper dredging and disposal activities.

The North Fairway dredging work would be restricted during periods of fish migration. This restriction may be from 1 March to 15 October of any given year. Based on the restrictions placed on projects occurring in the same area, it is likely that in-water work will not be allowed from 1 March to 14 June of any given year for juvenile threatened salmonids, and from 16 August to 15 October of any given year for adult salmon migration. Restrictions on in-water work for the protection of coastal cutthroat trout may be from 1 May to 1 September of any given year. Construction activities will also likely be physically restricted and will not be allowed within 0.5 mile of Deadman Island. This restriction may also apply to other islands.

Other timing restrictions may apply for crab (these restrictions are under development by WDFW) and brown pelican roosting (limiting activities in the summer). It is possible to avoid these timing restrictions by providing other types of mitigation. For example, observers may be required for the dredging and disposal activities during brown pelican roosting season. The observer

would have the authority to shut down the operation if it proves detrimental to the pelicans.

Another constraint is the time required to obtain permits. Currently, the timing from submittal of a BA, which triggers formal consultation with the services, to concurrence by the Services is approximately 12 months. The time delay is attributable primarily to the backlog of BAs submitted to the Seattle District and the Services for their review. The Services will likely determine that formal consultation is required on the project, due to the use of a hopper dredge, which may increase the time to receive concurrence. Also, receipt of all responses from WDOE may require additional time once District review is complete. Bidding and contracting processes will require additional process time.

Opportunities to achieve positive environmental effects were identified previously (Report 1, Appendix H) for each of the alternative disposal sites, A, B, C, D, D1, and E. Beach nourishment may slow the erosion of the shoreline, resulting in reduced turbidity and increased habitat availability (A and B). The placement of dredged material along the east side of the SR-105 Emergency Stabilization Project may help to nourish a shoreline dune that was breached during a 1998 extreme tide (D-1). Similarly, protection from erosion for a retreating stretch of shoreline may be accomplished by placing dredged material west of the SR-105 groin (C) or east of the groin (D). Placement of the dredged material along the north side slope of the North Channel (E) could stabilize the channel side slope and assist in the growth of upper beach profile.

North Fairway/SR-105

Description of North Fairway/SR-105 alternatives. The primary construction activities for Alternative 3H-a are dredging and disposal of the dredged material. Alternative 3H-b will also raise the level of an existing underwater dike that is part of the SR-105 Emergency Stabilization Project. The dredging operation will occur primarily on the entrance bar, and the resulting channel will be in a fixed position. Both North Fairway/SR-105 dredging alternatives are combined with disposal site alternatives A, B, C, D, D1, and E. Basic descriptions of the variations of dredging the North Fairway channel are given in Table 5-3.

Table 5-3
North Fairway/SR-105 Options

Alternative	Dredging Options
3H-a	Dredge a straight 26-ft deep by 500-ft-wide channel.
3H-b	Dredge a straight 26-ft deep by 500-ft-wide channel, and raise by 16 ft (from a depth of 18 ft to 2 ft) the existing spur dike located in the North Fairway adjacent to SR-105.

Environmental review. The Seattle District will prepare a NEPA EA for the preferred alternative. The primary factors to evaluate for impacts to the environment from the project are:

a. Species and habitat at the dredging location.

b. Species and habitat at dredged material disposal location(s).

c. Species and habitat in areas affected by raising the existing dike adjacent to SR-105.

The sediment dredged from this location, as with the other dredging sites, is suitable for open-water disposal, as well as for beneficial uses.

Permitting process. The following approvals and permits must be obtained prior to dredging and disposal:

a. EA (leading to FONSI or FEIS).

b. 404(b)(1) alternatives analysis to be completed by the Environmental Resources Section of the Seattle District.

c. ESA Section 7 consultation with the Services for dredging and disposal alternatives.

d. 401 WQC from WDOE.

e. CZM Consistency Determination with concurrence from WDOE.

f. State Response Letter with comments from WDFW.

Constraints and opportunities. As with the alternatives previously discussed, constraints to Alternatives 3H-a and 3H-b are primarily driven by ESA and sensitive species concerns. Direct impacts to species include direct mortality or stress from noise, entrainment, turbidity, decrease of dissolved oxygen, and coverage by disposal material. Indirect impacts identified in the environmental review of the SR-105 project included interference with migration patterns, prey resources, and increase of juvenile salmon predation. Environmental impacts from dredging are reduced due to the depths of dredging and the distance from the shoreline; best management practices (BMPs) will also reduce impacts. Raising the dike (3H-b) poses added concerns regarding the use of the area by threatened fish species and impacts to fish migration.

The same BMPs or actions as those presented in the previous section for the conservation of the species are repeated in an abbreviated form as follows:

a. Mitigation is likely to be required for any impacts caused to crab.

b. Dredging and disposal may be restricted to hydraulic dredging with direct disposal only above elevation +3 ft mllw.

c. Dredging work would be restricted during periods of fish migration. This restriction may be from 1 March to 15 October of any given year. Based on the restrictions placed on projects occurring in the same area, it is likely that the work will not be allowed from 1 March to 14 June of any given year for juvenile threatened salmonids, and from 16 August to 15 October of any given year for adult salmon migration. Restrictions on in-water work for the protection of coastal cutthroat trout may be from 1 May to 1 September of any given year.

d. Construction activities will also likely be spatially restricted and will not be allowed within 0.5 mile of Deadman Island. This restriction may also apply to other islands.

e. Other timing restrictions may apply for crab (these restrictions are under development) and brown pelican roosting (summer).

The same opportunities as those listed in the previous section exist for each of the alternative disposal sites, A, B, C, D, D1, and E. They are presented in abbreviated form as follows:

a. Beach nourishment may slow the erosion of the shoreline, resulting in reduced turbidity and increased habitat availability (A and B).

b. The placement of dredged material along the east side of the SR-105 Emergency Stabilization Project may help to nourish a shoreline dune that was breached during a 1998 extreme tide (D1).

c. Similarly, protection from erosion for a retreating stretch of shoreline may be accomplished by placing dredged material west of the SR-105 groin (C) or east of the groin (D).

d. Placement of the dredged material along the north side slope of the North Channel (E) could stabilize the channel side slope and assist in the growth of upper beach profile.

Findings

There do not appear to be permitting issues that would prevent any of the alternatives from being considered. However, three constraints have been identified:

a. Wave exposure of the dredging equipment generally requires dredging to be completed by early October of any given year, and the adult fish closure may interfere with that timing. Arrangements with WDFW would need to exempt the Seattle District from this timing restriction.

b. All action alternatives will likely undergo formal consultation (formal conference) with the Services because hopper dredging is a part of the alternatives. The wave environment in the work area during the anticipated work window and volume of dredging will require that the dredging be accomplished hydraulically. This method has been discouraged by the Services in Willapa Bay; however, for safety and other considerations, clamshell dredging is not practical for any of the alternatives. If formal consultation is required, a Biological Opinion (BO) must be prepared by NMFS and USFWS, and the BO may contain unanticipated design or construction conditions to the project.

c. Mitigation for impacts to crab will likely be required. Historically, this mitigation has taken the form of placement of oyster shell in the disturbed area or in established crab beds.

Matrix and Time Line

Table 5-4 is a compilation of the information provided in this chapter, arranged by action alternative and disposal site alternative.

Table 5-5 shows the anticipated permitting time lines for the alternatives. The best-case time line is based primarily on the assumption that the dredging and disposal sites will require routine formal consultation with the Services and will not require an EIS to be completed. This outcome is likely for Alternatives 3A, 3B, and 3H-a. The worst-case time line shows how the project is affected if formal consultation is protracted and if additional environmental review is necessary, which may be necessary for Alternative 3H-b. The time lines are not static, and the schedule shown for individual actions may differ from the actual time required. Environmental review and permitting is expected to require at least 18 months and no more than 24 months.

Table 5-4
Permits Required for Channel Alternatives

Action Alternative	Disposal Alternative	Permits/Approvals	BMPs/Constraints
3A 3B 3H-a 3H-b	A B C D D1 E	EA (FONSI, FEIS) 404(b)(1) alternatives analysis Biological Evaluation (BE)/ consultation with Services for all disposal site alternatives (PBA utilized for action alternatives) 401 WQC/CZM Consistency Determination State Response Letter from Ecology: Comments from WDFW Shoreline comments	Fish closure from 3/1 to 6/15 for juvenile salmonid migration; currently also from 8/16 to 10/15 for adult migration; no disposal above –30 ft (mllw) from 3/1 to 6/15. Coastal cutthroat may be protected with fish closure from 5/1 to 9/1. Dredging may be limited by restrictions on hopper dredge from 8/15 to 10/15. Work can occur no closer than 0.5 mile to Deadman Island. Crab mitigation likely required. Working outside June to September increases the likelihood that waves and currents could interfere with disposal operations. Dredging placement restricted to hydraulic dredging with direct disposal only above +3 ft (mllw). Difficult to coordinate timing of dredging and placement of materials for beach nourishment.

Table 5-5
Best- and Worst-Case Time Lines

Best-Case Time line

Time in Months from Beginning of Permitting

1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24
Crab Survey		EA (Public Comment), 404 (b)(1) Alternatives Analysis				FONSI Issued	SOF Pub-lished	ESA Formal Consultation												401 WQ C/C ZM			

Worst-Case Time line

Time in Months from Beginning of Permitting

1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24
Crab Survey		EA (Public Comment), 404 (b)(1) Alternatives Analysis						EIS, ESA Formal Consultation, ROD Published												401 WQC/CZM			

References

Kraus, N. C., (Editor). (2000). "Study of navigation channel feasibility, Willapa Bay, Washington," Report 1, Technical Report ERDC/CHL TR-00-6, U.S. Army Engineer Research and Development Center, Coastal and Hydraulics Laboratory, Vicksburg, MS.

6 Alternatives, Summary, and Conclusions[1]

The screening process in Report 1 (Kraus 2000) produced four groups of alternative designs for the Willapa Bay navigation channel:

a. "No action" alternative.

b. North Fairway alternatives.

c. SR-105 dike alternatives.

d. Middle Fairway alternatives.

The action alternatives each involve maintaining a channel over the bar at the mouth of Willapa Bay. The "no action" alternative in Report 1 is the "existing procedure" because it is the continuation of the current activities, which does not include dredging or other construction, but only data collection. Alternatives shown to remain feasible in the previous chapters are listed in the following section. This chapter also summarizes the findings of measurements and modeling of processes at Bay Center Entrance Channel.

Alternatives

Studies completed in this report have narrowed the previous-referenced alternatives and placed them into one group of alternatives, in addition to the "no action" alternative. The original alternative groups 1 and 2 are combined into one group, the North Fairway alternatives. The Middle Fairway alternatives are eliminated from further consideration because, through data collection and analysis, it became apparent that a stable channel at this location would require significant amounts of capital and maintenance dredging, whereas a 26-ft-deep[2] channel in the North Fairway might require only minor maintenance. Technical analyses in the present study applied engineering criteria to retain or to eliminate previously developed alternatives, as a basis for a NEPA analysis to be conducted in a future project phase. The alternatives remaining at the conclusion of the present study are as follows:

[1] Written by Nicholas C. Kraus, U.S. Army Engineer Research and Development Center, Coastal and Hydraulics Laboratory, Vicksburg, MS, and David P. Simpson, Pacific International Engineering PLLC, Edmonds, WA.

[2] All depths in this chapter are referenced to mean lower low water (mllw).

"No action" alternative

Alternative 1: Existing procedure or the status quo.

The first alternative identified in Report 1 was a continuation of existing procedures, which is based on the assumption that it is not feasible to maintain a navigable depth of 26 ft over the Willapa Bay entrance bar to restore commercial navigation by dredging. If selected, bathymetry would be surveyed to monitor the channel depths and location, and relocate navigation buoys for users. No channel over the entrance bar would be dredged.

Action alternatives - North Fairway group

Alternative 3A: 26-ft-deep by 500-ft-wide channel, fixed location.

Alternative 3B: 26-ft-deep by 500-ft-wide migrating channel, with a minimum 1,500-ft width in the S-curve.

Alternative 3H-a: 26-ft-deep by 500-ft-wide channel with no change in the existing SR-105 dike.

Alternative 3H-b: 26-ft-deep by 500-ft-wide channel, with the SR-105 dike crest raised from 18-ft depth to 2-ft depth.

Channel depths previously listed do not include allowance for overdepth dredging, which might provide up to an additional 2 ft of depth at the time of dredging.

Alternatives 3F and 3G were eliminated from further consideration because of the apparent trend in the channel to develop a self-maintaining dimension in the 26- to 28-ft depth range, as evidenced by recent bathymetric surveys.

Summary

Willapa Bay navigation channel

This study documented a historical trend of North Channel migration and Willapa Bar dynamics (North Channel) prior to construction of the SR-105 Emergency Stabilization Project in 1998. Monitoring and analysis revealed the range of the unrestricted migration of the north tidal channel, breaching of the Shoalwater Spit, and formation of extensive shoals and submerged islands that became a source of a great amount of sediment in the inlet system. This sediment eventually became part of the navigation channel infill and dredging requirement of the North Channel. Monitoring after construction of the SR-105 Emergency Stabilization Project, indicated that processes controlling outer bar channel position and infill rate are related to decadal-scale oceanographic processes as well as tidal channel hydraulics on a diurnal scale.

The Willapa Bay entrance and bar are subjected to complicated hydrodynamic and morphological processes. The scale of channel changes along the entire channel is variable. To distinguish these changes and for purposes of future targeted monitoring, the navigation channel is expected to display different types of changes in two identifiable sections: the inner section, the part of the

channel eastward from the E735000 state plane coordinate, which is approximately 3 to 4 miles long; and the outer section, the westward part of the channel through the outer bar, approximately 3 to 4 miles long, as shown in Figure 3-6.

Inner channel movement is more deterministic and predictable. This portion of the channel has become stabilized in the sense that it no longer appears to have unconstrained movement northward in the vicinity of North Cove. Surveys show that the channel thalweg has moved 500 to 1,500 ft southward since project construction in 1998. Outer section changes are more random. The range of alongshore movement of the outer bar channel is believed to have become more restricted following dike construction and apparent stabilization of the inner section. With the inner section of the channel controlled or influenced by the project, the outer section of the channel is likely to become more constrained also.

One preliminary indication of this phenomenon is in the sediment volumes within the channel templates calculated with the series of bathymetric surveys from 1998 through 2001, shown in Table 3-1. Sediments that are thought to constitute the shoals that breach and migrate back into the entrance and ultimately into the channel are greatly reduced in volume, and the range of outer channel migration distance is expected to correspondingly decrease. The reduced volumes of sediment in the channel templates listed for Alternatives 3A and 3H in Table 3-1 might be indications that the stability of the inner channel influences the range of outer channel migration. A longer record of bathymetric surveys will confirm the relationship between inner and outer channel stability.

Bay Center Entrance Channel

Planned maintenance dredging of Bay Center Entrance Channel provided the opportunity to monitor the bathymetry, hydrodynamics, and sediment flux in the channel to document changes in morphology and sediment transport processes following dredging. The monitoring enabled investigators to infer processes that are responsible for features in the Bay Center Entrance Channel and provide high-quality data for validation of the hydrodynamic model's capability to simulate behavior of a dynamic natural system. Dredging removed 178,000 cu yd from the channel in a 40-day period. Channel depth was excavated from 0 to 15 ft at its most constricted location. In the time from before dredging to after, the flows at the middle and east instrument stations at the side of the channel changed from flood-dominated to ebb-dominated. The west station at the confluence of Nahcotta Channel and Bay Center Entrance Channel remained flood-dominated. The flow and transport asymmetry induced a net transport of sediment toward Nahcotta Channel from Goose Point. Flow deceleration observed to occur between the middle and west stations is inferred to be the mechanism causing deposition in the reach that historically has shoaled most quickly.

Geomorphic processes act in parallel with the hydrodynamics previously described. The location where the main east-west channel connects with the northwest channel has shifted repeatedly between northern and southern positions. Historical surveys indicated that the channel moves northward and deepens or decreases the rate of shoaling during the summer. During the winter,

the channel at this location moves southward and experiences rapid shoaling. The channel returns to the northern location the next summer.

Conclusion

Phase II of the Navigation Channel Feasibility Study documented here narrowed the alternative channel designs to one set of alternatives, in addition to the "no action" alternative. Although hydrodymanic and geomorphologic processes at the entrance to Willapa Bay have been more clearly documented in the past 3 years, it is considered premature to select a preferred alternative at this time. Measurements indicate that areas in the entrance are undergoing long-term change in response to the SR-105 structure, and the natural deepwater channel might become even more reliable as a navigation channel in the near-term. The conclusion of the study is to continue the existing procedure until data justify recommending a preferred alternative. The Phase II study participants conclude that a program of targeted monitoring of the Willapa Bay entrance, including further analysis of the remaining alternatives, should be undertaken before a recommendation of a preferred alternative navigation channel design can be made.

Further study is recommended to determine the limits of the outer channel migration zone and the range of sediment volumes in the channel templates, and to verify that the inner channel is now relatively fixed in location. These outer channel processes may be driven by large-scale geomorphological processes, which cannot be predicted with existing hydrodynamic models. Long-term monitoring is the most direct and reliable means of analyzing and quantifying the morphological expression of these processes. A targeted monitoring program should be developed from the following recommendations:

a. Continue bathymetric monitoring of the entrance area that encompasses channel Alternatives 3A, 3B, and 3H twice per year, and process and compare the data with previous channel positions and sediment volumes within channel templates.

b. Continue monitoring the vicinity of the SR-105 underwater dike and adjacent shoreline because the structure appears to have a stabilizing influence on the inner portion of the entrance channel and North Cove shoreline.

With continued, targeted monitoring, it will be possible to recommend an optimum alignment and more confidently predict the volumes of maintenance dredging (if required).

The basis of the recommendation for further monitoring and analysis is the conclusion that the geomorphologic processes at the entrance to Willapa Bay are in transition. Progressive changes have been occurring in the deepwater channel since construction of the SR-105 structure, and the North Channel is developing toward a relatively more stable condition naturally. A relatively stable channel alignment in the North Fairway will form once adjustment to the SR-105 dike is complete. The stable channel alignment cannot be accurately predicted at this time, but is expected to form between the northern position of Alternative 3B and the southern limit of Alternative 3H. Equilibrium channel depth also appears to still be forming. Because the boundaries as well as the time frame of future

stable alignment and depth are not predictable within existing observations, a targeted monitoring program of 2 to 5 years is recommended. Selection of a final alternative and estimation of volumes of maintenance dredging (if required) will result from the monitoring and will form the basis of an economic cost-benefit analysis and NEPA process.

Continuation of Bay Center Entrance Channel bimonthly hydrographic surveying and twice-yearly aerial photography is recommended. Geomorphic processes likewise seem to dominate the changes in location of the Northwest Channel of Bay Center Entrance Channel. Location changes appear to be linked to seasonal cycles. Changes in channel depth at the location of historical shoaling appear to be related to changes in location. Continued monitoring of bathymetry will be useful to the Corps' research elements in improving numerical modeling capabilities and to the Seattle District in improving efficiency of maintaining the channel.

References

Kraus, N. C., (Editor). (2000). "Study of navigation channel feasibility, Willapa Bay, Washington," Report 1, Technical Report ERDC/CHL TR-00-6, U.S. Army Engineer Research and Development Center, Coastal and Hydraulics Laboratory, Vicksburg, MS.

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14. ABSTRACT

This report presents results of Phase II of a study performed for the U.S. Army Engineer District, Seattle, to determine the technical feasibility of maintaining a reliable bar or entrance navigation channel into Willapa Bay, Washington. The study was authorized by the Seattle District in cooperation with the Port of Willapa Harbor under a Partnering Agreement. The Phase I study was an intensive effort to understand the physical processes at the study site, collect data, and establish numerical simulation models of the waves and currents at the entrance. Numerous alternatives for creating and maintaining the most reliable entrance channel were also identified and screened. The Phase II study describes the results of ongoing monitoring of the existing natural navigation channel, changes in bathymetry, and refinements to the numerical models. Also included is an application of the monitoring and modeling technology to the entrance channel leading from Willapa Bay to Bay Center, as small fishing harbor. The entrance area of this shallow-draft navigation channel served as a convenient surrogate for improving the predictive technology, as well as advancing understanding of sediment transport processes in the bay and the deep Willapa Bay entrance channel.

15. SUBJECT TERMS

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Circulation model	Navigation channel	Surface-Water Modeling System	
Dredging	Sediment shoaling	Tidal inlet	

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